ttX/tX production at CMS

10th Edition of the Large Hadron Collider Physics Conference

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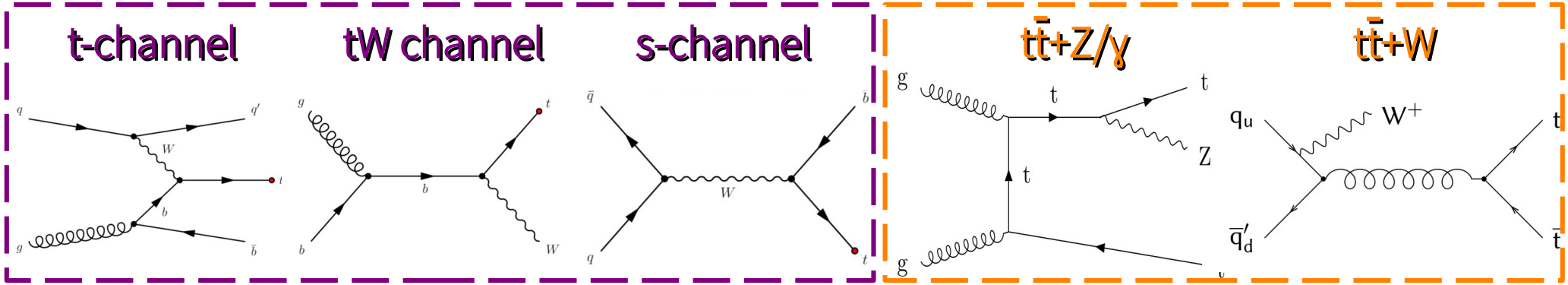
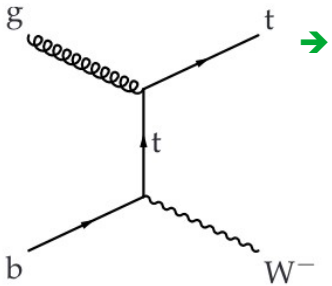
CMS Compact Muon Solenoid

2022 LHCP TAIPEI Online

Understanding the **top quark properties** and **production mechanisms** is one of the core elements of the **LHC** physics programme.

- At the LHC, top quarks are mainly produced through two different mechanisms:
  - **Electroweak** production of single top in association with weak bosons (t+X, where X=W,Z,γ).
  - Top-antitop quark pair production ($t\bar{t}$) via the **strong interaction.** At the LHC it is also possible to consider EWK interactions at tree level through the production of $t\bar{t}$ in association with vector bosons ($t\bar{t}$+X, where X=W,Z,γ).
- In this talk, a review of single top and top-quark pair production studies is presented.





➔ The tW process

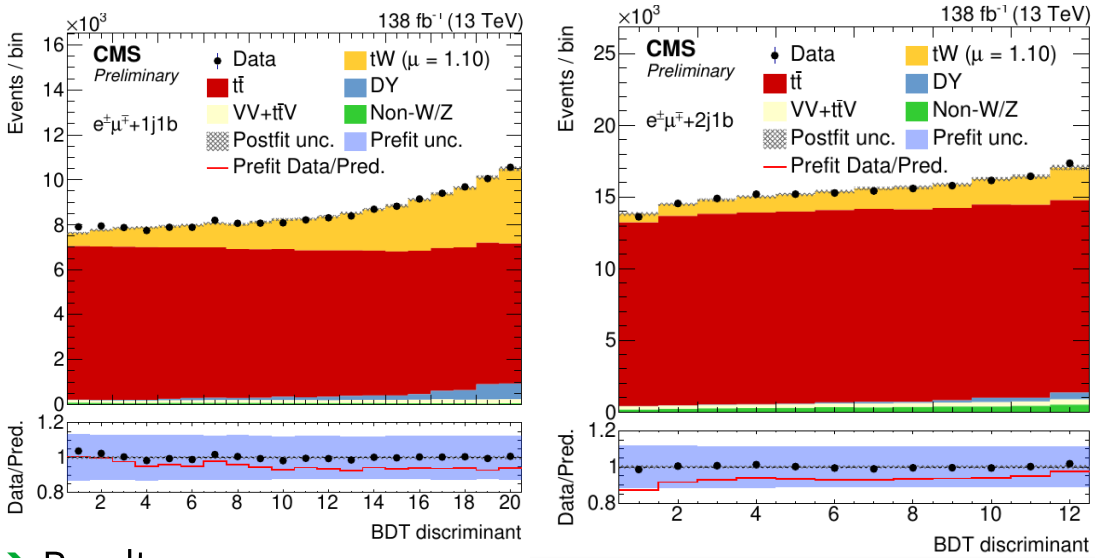
- Interference with $t\bar{t}$ at NLO in QCD.
- Diagram Removal scheme is used to model the tW.

➔ Methodology for the inclusive measurement

- Target of OSDF[1] **lepton pairs** ($e^{\pm}\mu^{\mp}$).
- Remaining events are **classified according to** different **jet** and **b tag multiplicities.**
- Independent **BDTs** are trained to discriminate signal and background events.

➔ Signal extraction

- Simultaneous **Binned maximum likelihood fit** to **three BDT discriminants.**



➔ Results

$\sigma(tW) = 79.2 \pm 0.8\ (stat) \pm 7.1\ (syst) \pm 1.1\ (lumi)$ pb.

$\sigma^{NNLO}(tW) = 71.7 \pm 1.8\ (scale) \pm 3.4\ (PDF)$ pb.

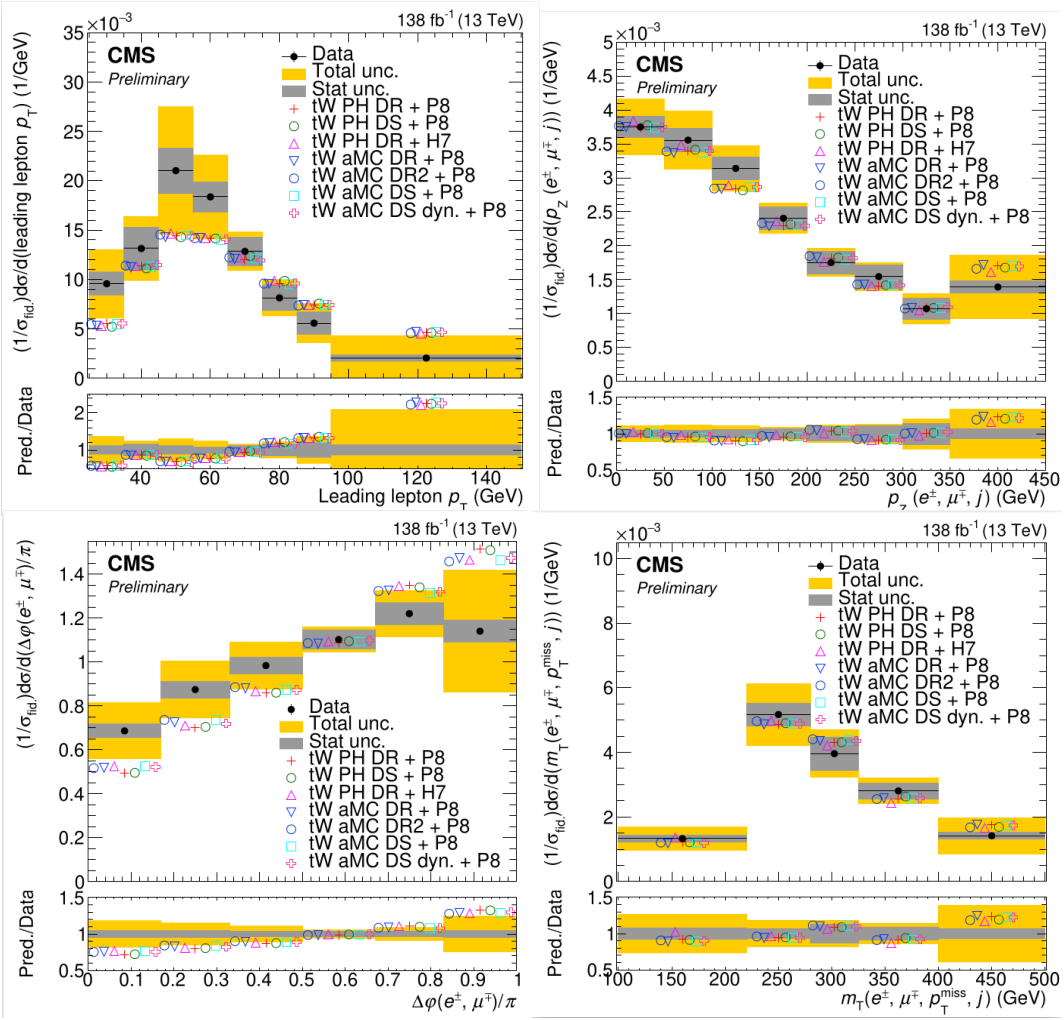
Good agreement with SM

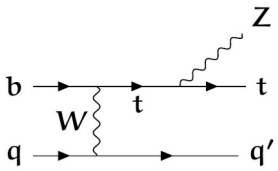
➔ Clearly dominated by systematic uncertainties

- Leading systs: JES, tW ME scales and FSR
- Difference in the modelling schemes is accounted for as well

1: Opossite Sign of the electric charge and Different Flavor

- In order to perform these measurements, **unfolding techniques** are required.
- These unfolding techniques can be performed at two levels: **particle level** and **parton level**.
- **Methodology for the differential measurement.**
  - The **phase space** defined for the differential measurement is taken as close as possible to the one used for the inclusive measurement.
  - The **particle level** is defined by the obtained particles after the generation of the strong process and after the parton shower.
  - Both the **signal extraction** and the **unfolding** for the differential cross section measurement are done with a **maximum likelihood** fit.
- **Agreement is overall good with respect to the expectations from the different generators.**





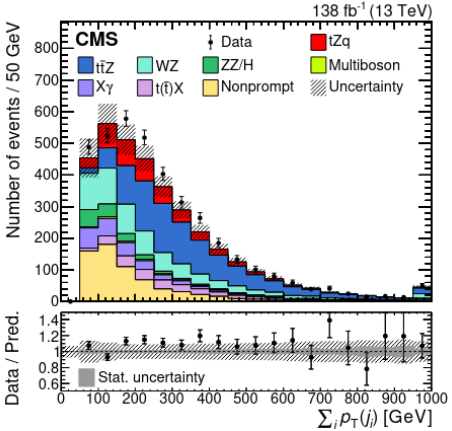
➔ The tZq process Offers the possibility of measuring tZ and $\bar{t}$Z separately.

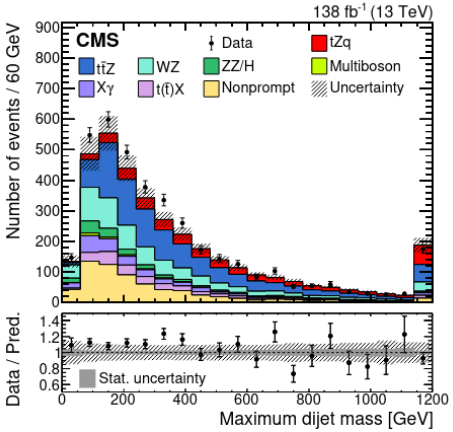
➔ Methodology for the inclusive measurement

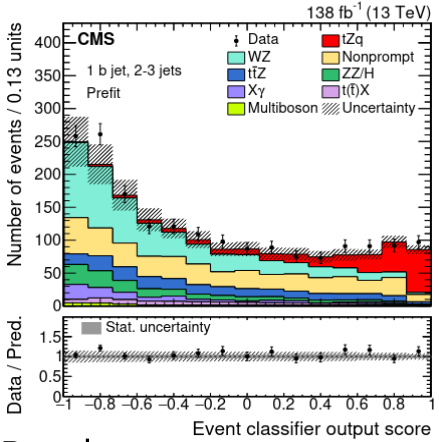
- Three leptons, 2 jets (at least one b tag). Further categorized in terms of jets and b tags.
- BDTs are used to enhance signal discrimination.

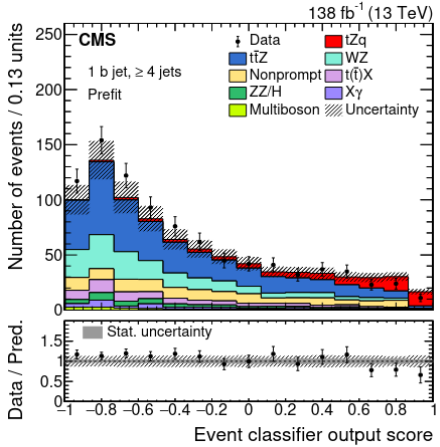
➔ Signal extraction

- Simultaneous Binned ML fit to BDT discriminants.









➔ Results

$\sigma(tZq) = 87.9 \pm 7.4\ (stat) \pm 6.7\ (syst)$ fb.

$\sigma^{NLO}(tZq) = 94.2 \pm 1.9\ (scale) \pm 2.5\ (PDF)$ fb.

Good agreement with SM

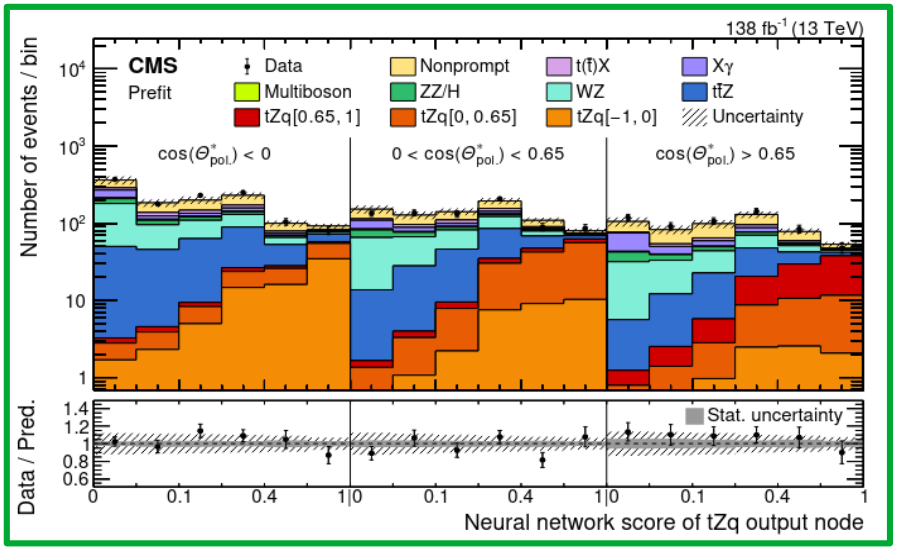
Able to measure separate t and $\bar{t}$ cross sections

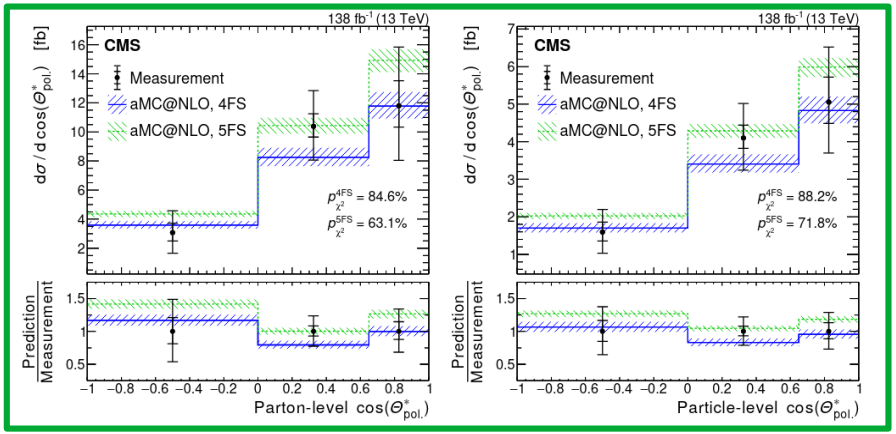
$\sigma_{tZq}(\ell_{t^+}) = 62.2 \pm 5.8\ (stat) \pm 4.1\ (syst)$ fb.

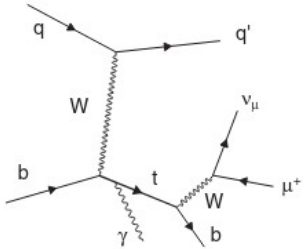
$\sigma_{tZq}(\ell_{t^-}) = 26.1 \pm 4.7\ (stat) \pm 2.9\ (syst)$ fb.

Improved total unc (11%) w.r.t. previous CMS measurement (that reported 14%) due to a **larger dataset** and **much better identification/classification techniques.**

- Event classification
  - Differential tZq cross section measurements are performed as a function of several observables at the **parton** and **particle** level → refered as **kinematic regions.**
    - $p_T(Z)$, $p_T(\ell_t)$, $m(3\ell)$, $\Delta\phi(\ell, \ell')$, $\cos(\theta^*_{pol})$, $m(t,Z)$, $p_T(j')$, $|\eta|(j')$.
- Methodology
  - A **likelihood-based unfolding** procedure is considered to measure the cross section in different kinematic region.
  - A multiclass neural network (NN) with 23 inputs and 5 output nodes is used to distinguish **tZq against ttZ.**
- Results
  - The measured distributions are **compared with theory predictions** of tZq at **NLO** in QCD for the **4 flavor-scheme (FS)** and **5FS**.
  - Finally, the spin asymmetry is measured as:
    - $A_\ell = 0.58 \pm 0.15(\text{stat}) \pm 0.06\ (\text{syst})$.





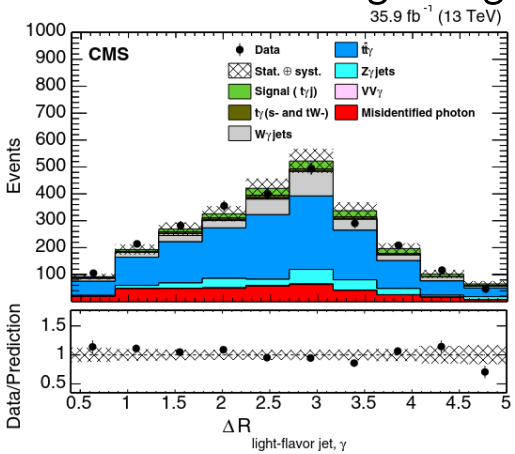


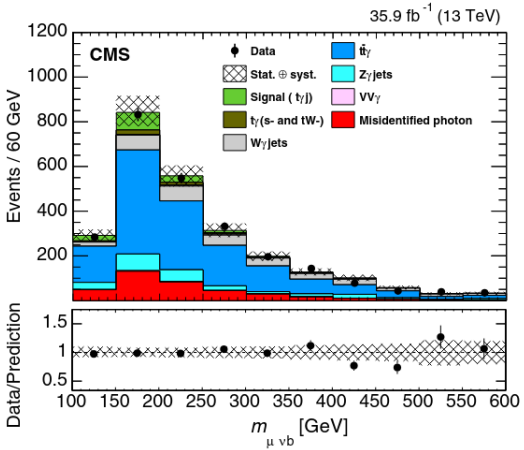
➔ Baseline signal selection

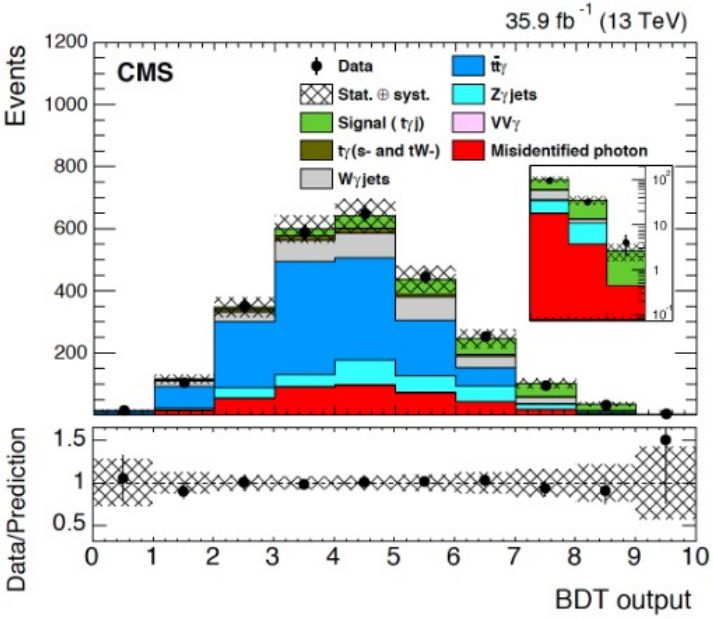
- Exactly one **isolated μ**, one **isolated γ**, **2j** (at least 1b).
- **γ isolation** is assured by requiring **ΔR>0.5** from any other particle in the event.

➔ Signal selection

- **Efficient signal/background discrimination** is achieved through the use BDTs.
- A simultaneous **binned likelihood** fit is performed on the **BDT distribution** in the **signal region** and a **$t\bar{t}$+γ control region**.







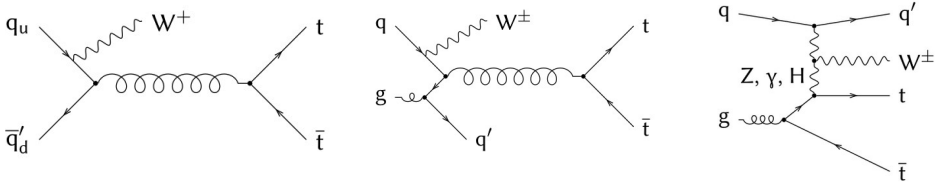
Measured fiducial cross section

σ(tγq) = 115 ± 17 (stat) ± 30 (syst) fb.

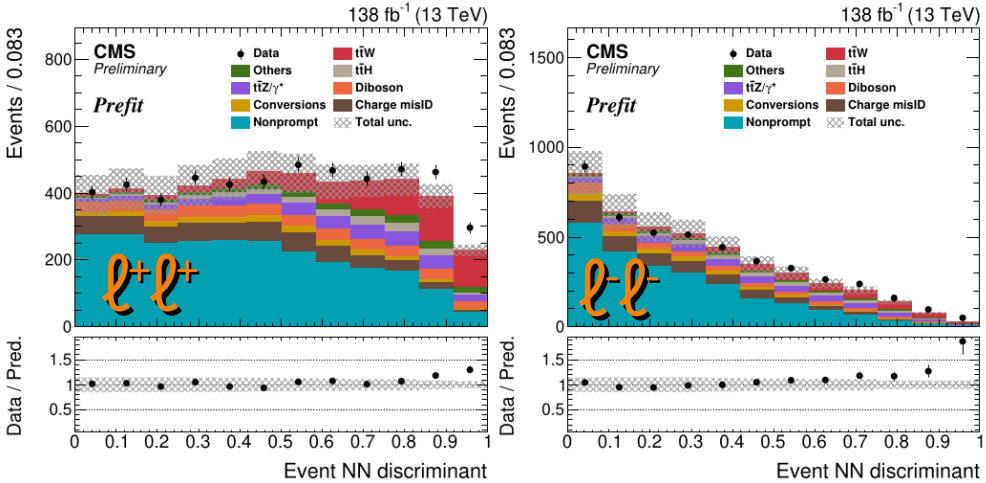
Expected fiducial cross section

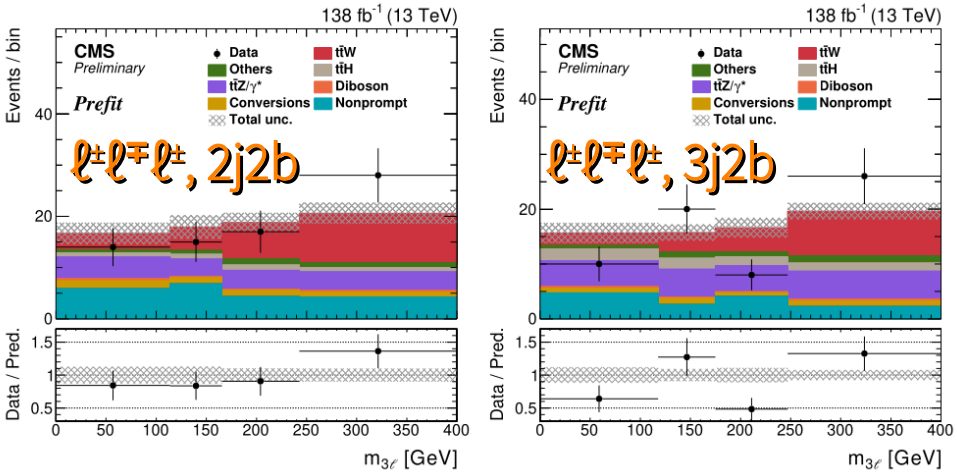
σ(tγq) = 81 ± 4 fb.

First evidence of tγq production by CMS at 4.4σ!

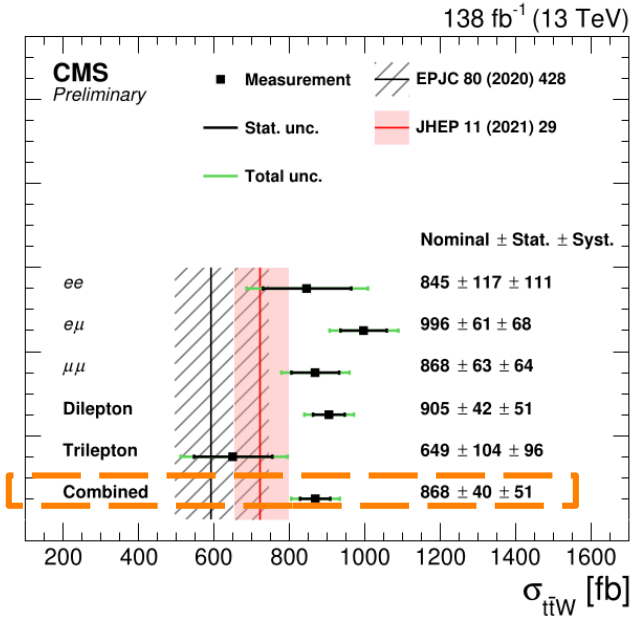


- **Same Sign dilepton (2ℓss) Strategy**: A **Deep Neural Network (DNN)** is used to distinguish between signal and background.
  - Architechture: (**128, 64, 4**).
  - **Lepton flavors** and **electrical charges** are used to further categorize events.
- **Trilepton (3ℓ) strategy**: **Twelve categories** are defined in terms of **jet** and **b tag multiplicities** and the **summed charge of the three leptons.**
  - $m_{3\ell}$ is used to discriminate signal from background.
- The **DNN output distributions** are then combined with the $m_{3\ell}$ distributions in a **binned profile likelihood fit** from where the value of the cross section is extracted.



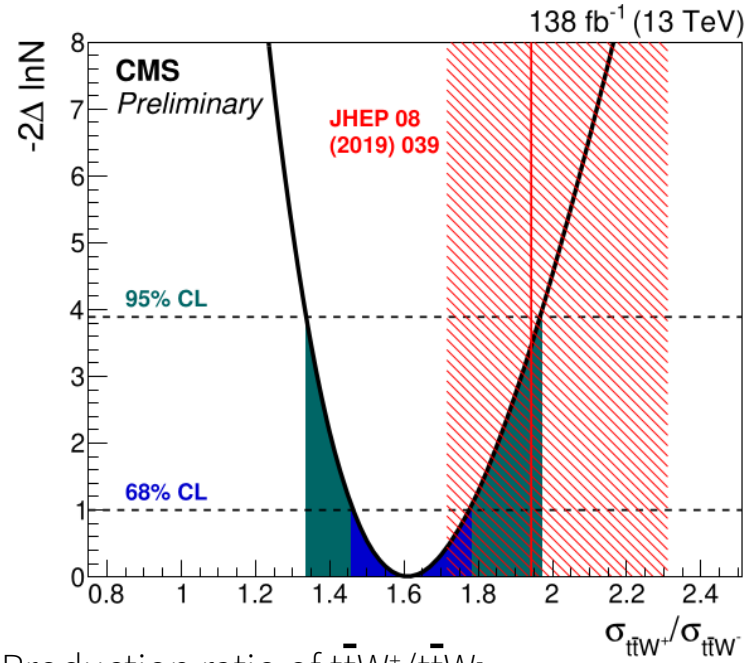


- Inclusive measurement
  - Results are compared to two theoretical predictions from EPJC 80 (2020) 428 and JHEP 11 (2021) 029.
  - 2016 measurement: [JHEP08 (2018) 011]
    - $\sigma(t\bar{t}W) = 800 \pm 120\ (\text{stat}) \pm 130\ (\text{syst})$ fb.

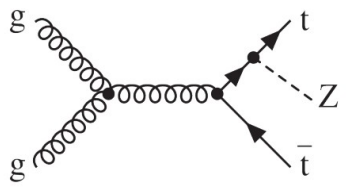


50% improvement on the systematic uncertainty with respect to 2016 measurement!

- Better background control
- Dedicated lepton MVA to target top-like events.



- Production ratio of $t\bar{t}W^+/t\bar{t}W^-$
  - Measured
    - $R_{t\bar{t}W^+/t\bar{t}W^-} = 1.61 \pm 0.15\ (\text{stat}) \pm 0.06\ (\text{syst})$.
  - Prediction at NLO+NNLL [JHEP 08 (2019) 039]
    - $R_{t\bar{t}W^+/t\bar{t}W^-} = 1.94 \pm 0.30$.
- First steps for a future ttW charge asymmetry.

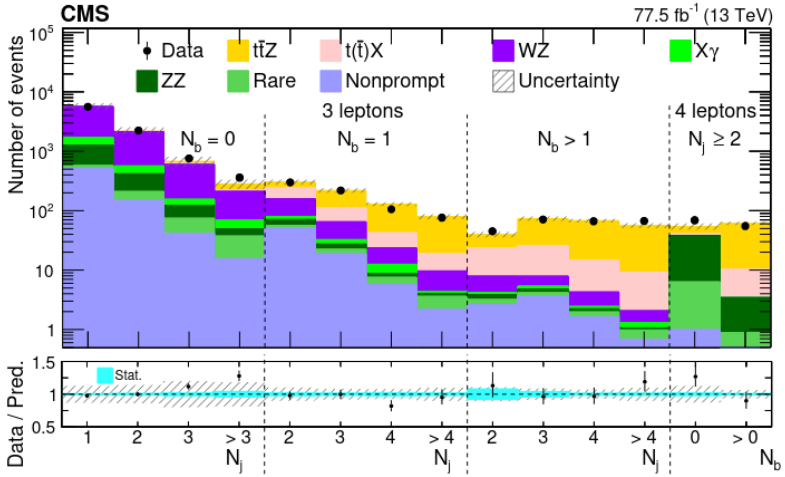


➔ Baseline signal selection

- Two different selections based on the number of leptons (3ℓ and 4ℓ) as well as other kinematic requirements.
- Further categorization in terms of jet and b tag multiplicities for both lepton categories.

➔ Signal extraction

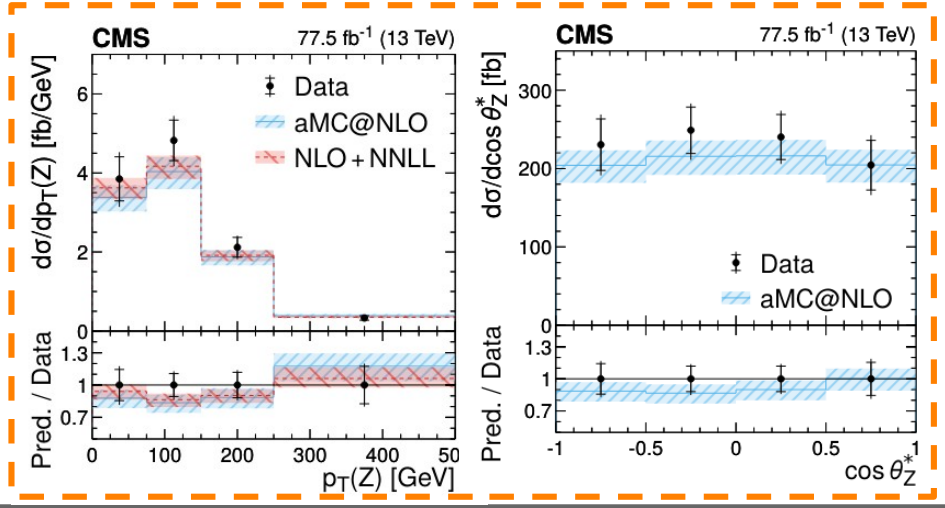
- For the inclusive measurement, a binned likelihood fit is performed to each analysis category.
- For the differential measurement, the cross section is measured as a function of $p_T(Z)$ and $\cos(\theta_Z^*)$.



Good agreement with SM

Lepton requirement	Measured cross section
3ℓ	$0.97 \pm 0.06\,(\text{stat}) \pm 0.06\,(\text{syst})$ pb
4ℓ	$0.91 \pm 0.14\,(\text{stat}) \pm 0.08\,(\text{syst})$ pb
Total	$0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})$ pb

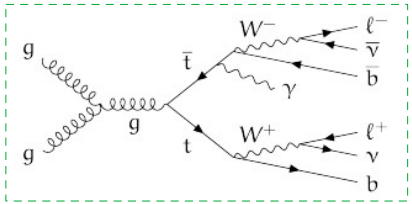
$\sigma^{NLO}(t\bar{t}Z) = 0.84 \pm 0.10$ pb.

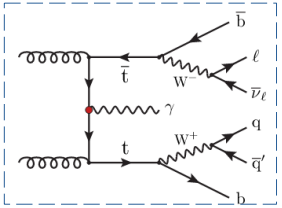


$t\bar{t}\gamma$ measurements

Inclusive cross section measurements targetting different lepton multiplicities

CMS-PAS-TOP-21-004
JHEP 12 (2021) 180





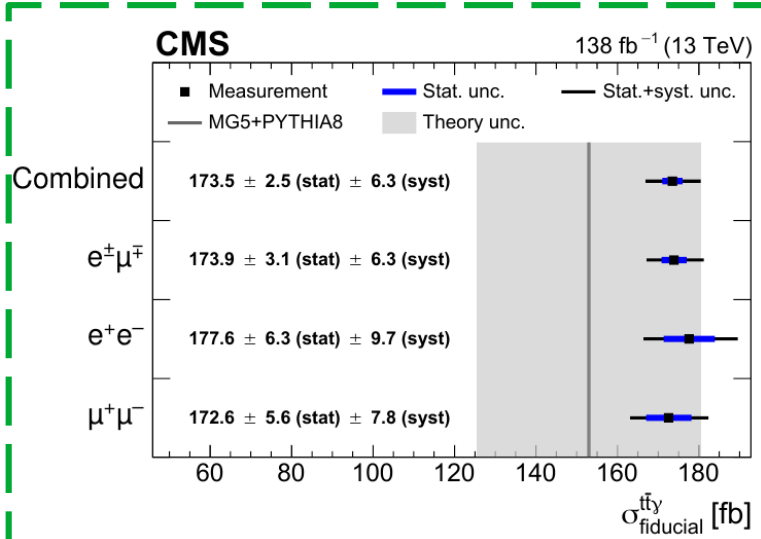
➔ Two separate measurements in final states with different lepton multiplicity.

- CMS-PAS-TOP-21-004 → Target multilepton final states.
- JHEP 12 (2021) 180 → Target single lepton final states.

} Run2 dataset (~138 fb^{-1})

➔ In both measurements, the methodology for the signal extraction is based on **background subtraction** and a **binned likelihood fit** .

- The reconstructed p_T of the photon is used for extracting the signal strength.
- The fit is performed to multiple signal and control regions for each data-taking period.



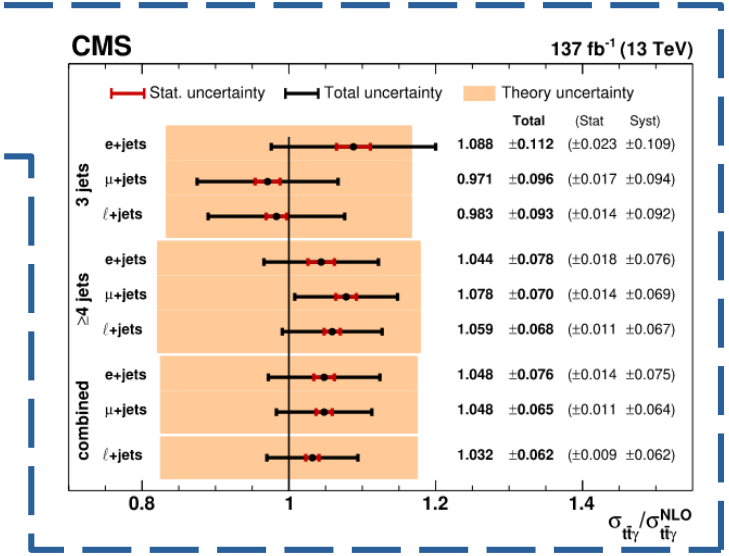
$\sigma(t\bar{t}\gamma)$ = 798±7(stat)±48(syst) fb

$\sigma^{NLO}(t\bar{t}\gamma)$ = 773±135 fb

Good agreement with SM

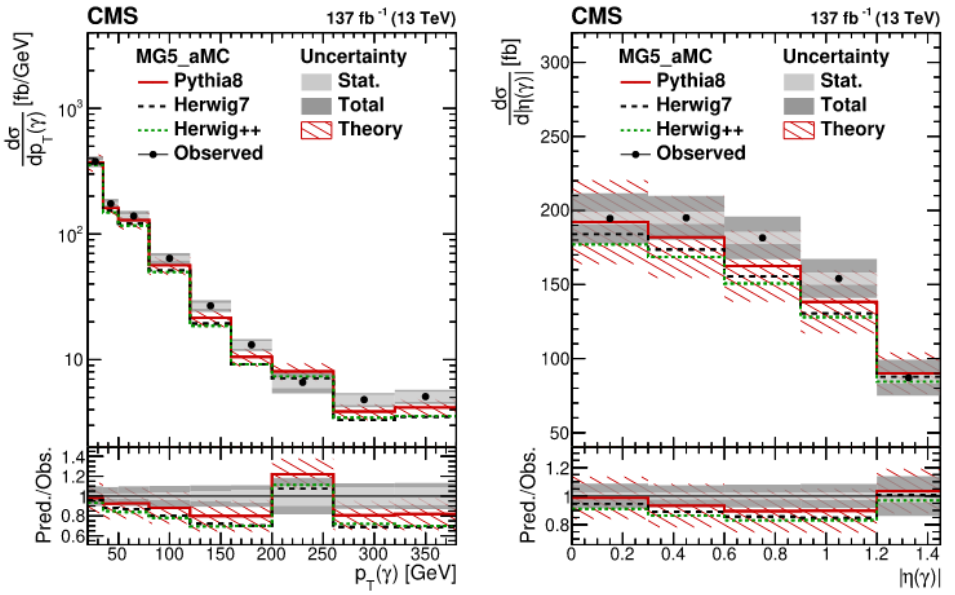
$\sigma(t\bar{t}\gamma)$ = 173.5±2.5(stat)±6.3(syst) fb

$\sigma^{NLO}(t\bar{t}\gamma)$ = 153±27 fb

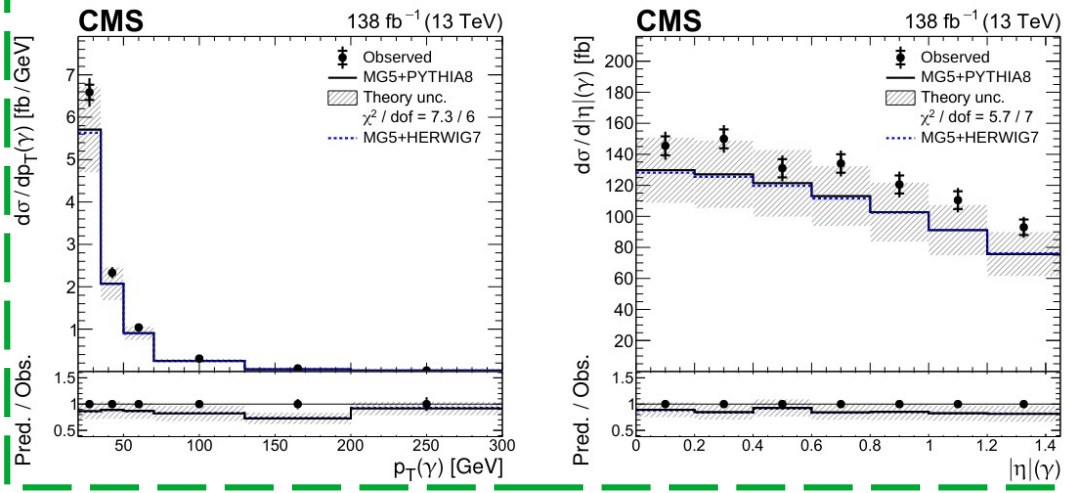


- Several observables based on kinematic properties of the objects involved (**photons, leptons and jets**) are used in both analysis to perform differential cross section measurements.

JHEP 12 (2021) 180

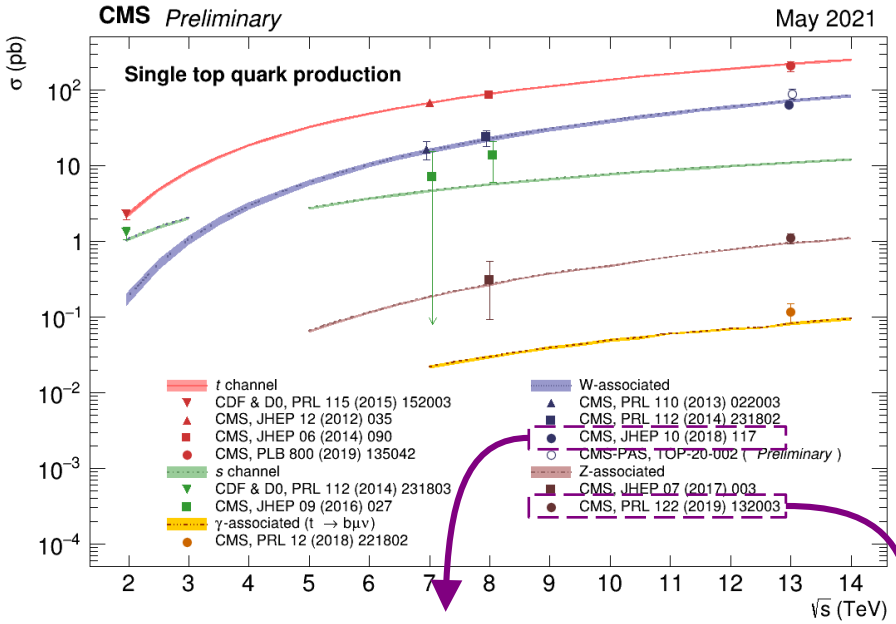


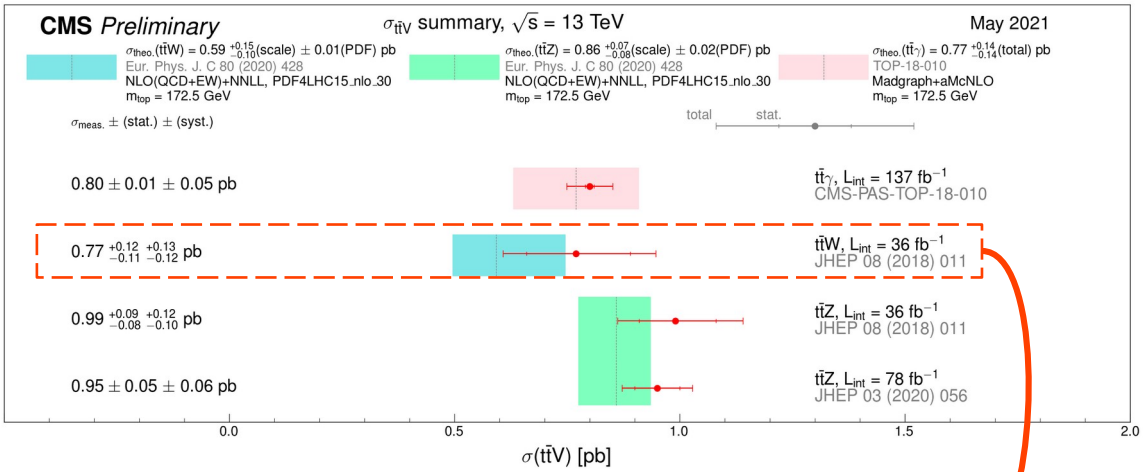
CMS-PAS-TOP-21-004



All the results are consistent with SM predictions at NLO calculated with `Madgraph5_aMC@NLO`.

- A review of the most recent CMS publications about ttX/tX production has been presented.





NEW: CMS-PAS-TOP-21-011 (ttW)

NEW: CMS-PAS-TOP-21-010 (tW)

NEW: JHEP 02 (2022) 107 (tZq)

- Stay tuned: New results with brand new data are on their way!

BACKUP

- On the single top production side
  - Measurement of rare single top production modes became more accessible at the LHC with respect to other hadron colliders such as Tevatron.
  - The study of single top quark production has several interesting features:
    - Interesting top quark couplings can be studied: t-γ, t-Z and t-W.
    - Differential measurements provide fundamental information and improvement on our knowledge about proton PDFs. (e.g CMS-PAS-TOP-21-010).
    - They also provide an optimal framework for measurement of top quark properties such as its mass or polarisation (e.g. JHEP 02 (2022) 107).
- On the top-antitop production in association with bosons side:
  - The large amount of LHC data recorded up to date, ~140 fb-1 (full run2 LHC data), allows probing very rare SM processes, very small production cross sections.
  - They are also highly sensitive to several EFT operators.
  - Processes such as ttZ and ttW are quite important backgrounds of many LHC searches.

Particle level definition

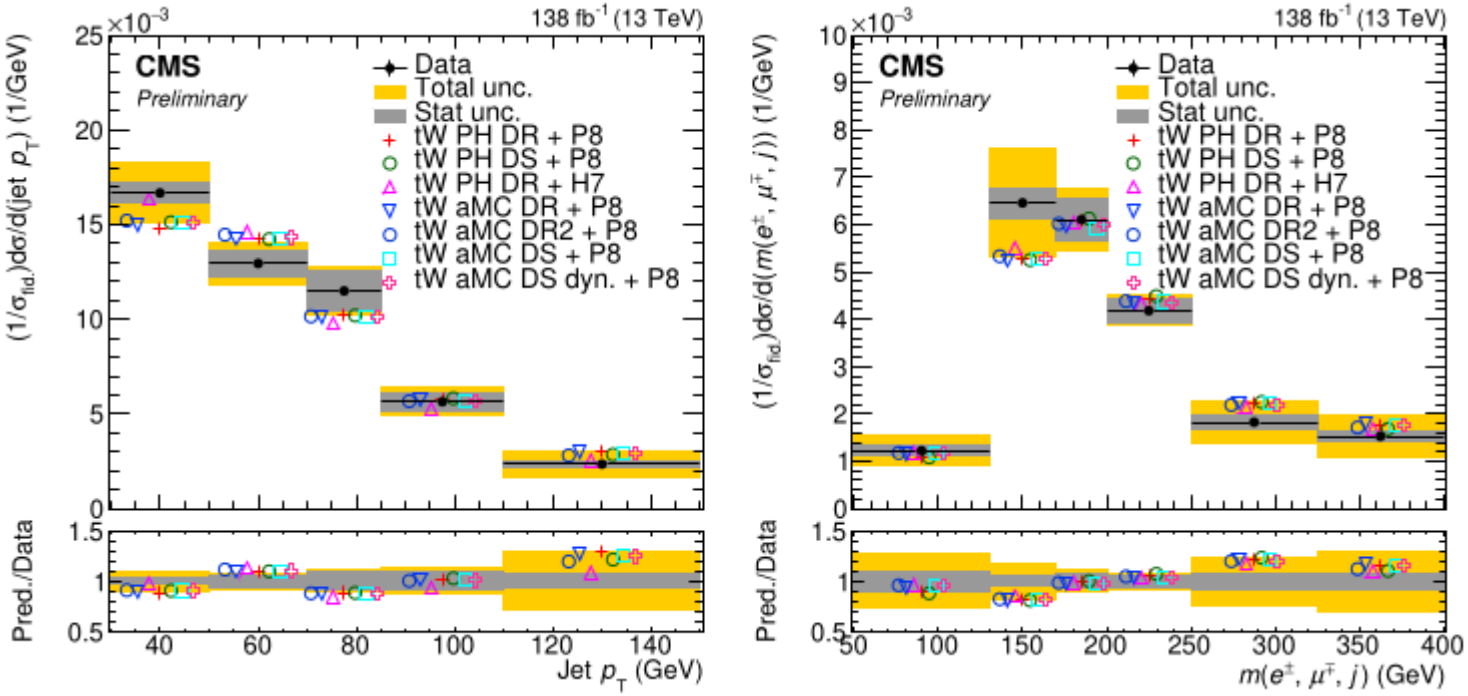
Muons		Electrons		Jets		Loose jets	
p_T (GeV)	$\|\eta\|$	p_T (GeV)	$\|\eta\|$	p_T (GeV)	$\|\eta\|$	p_T (GeV)	$\|\eta\|$
> 20	< 2.4	> 20	< 2.4 && (< 1.4442 || > 1.5660)	> 30	< 2.4	> 20 , < 30	< 2.4

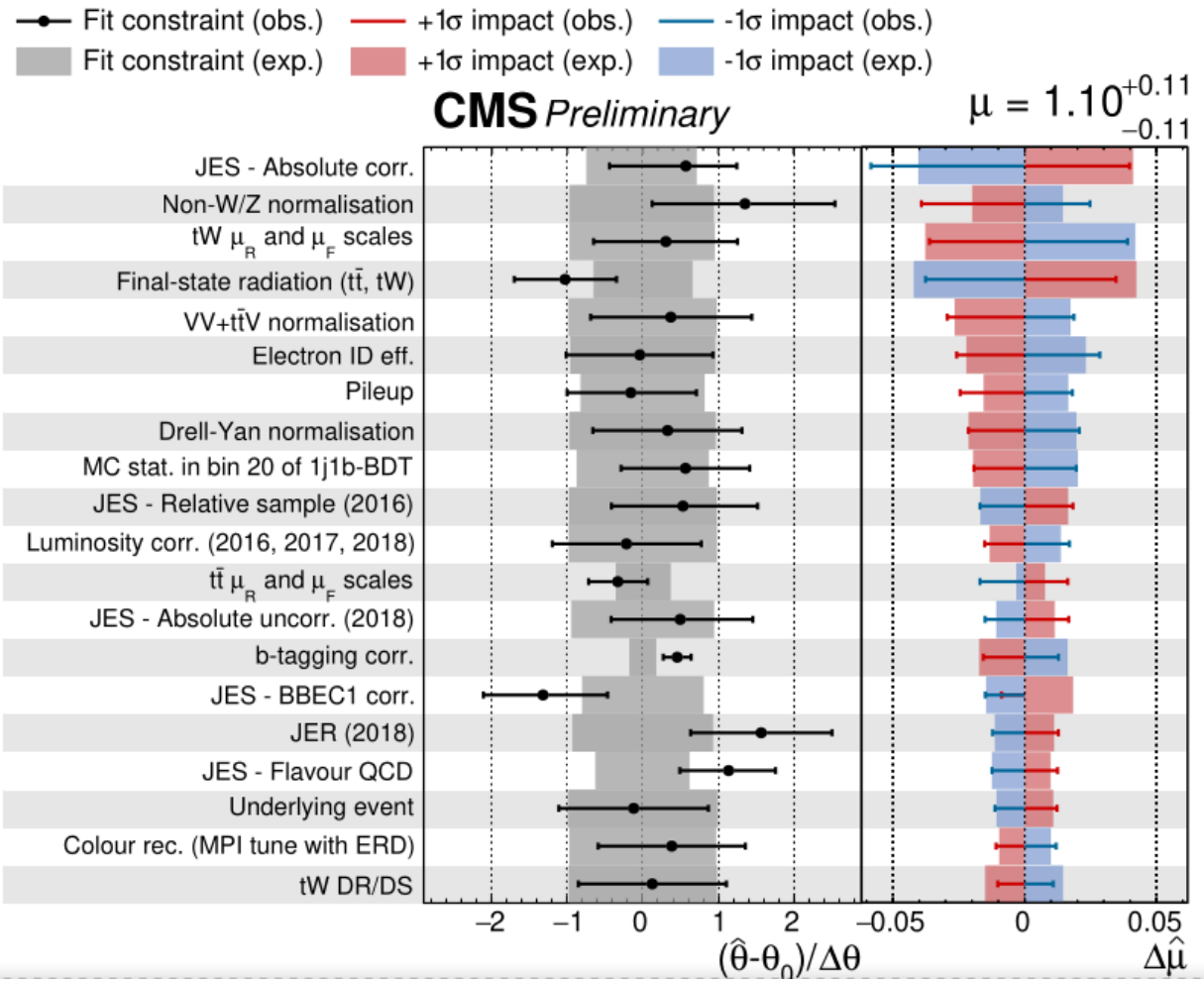
Table 2: Definition of the fiducial region.

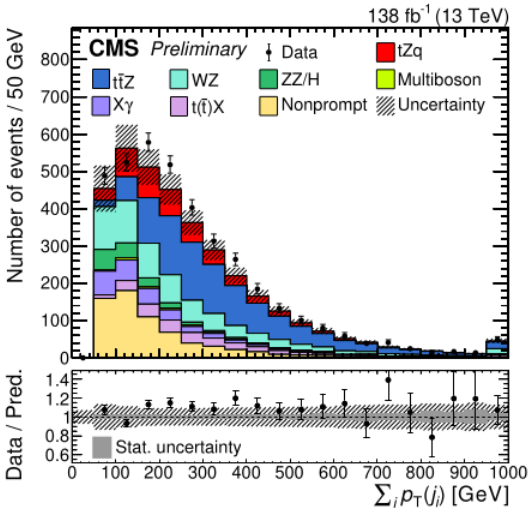
Number of leptons	≥ 2
Leading lepton p_T	> 25 GeV
Invariant mass of all dilepton pairs	> 20 GeV
Number of jets	1
Number of loose jets	0
Number of b jets	1

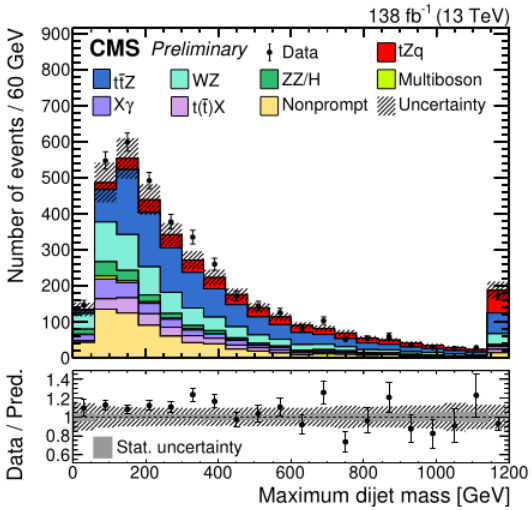
Observables to be studied

- Leading lepton p_T.
- Jet p_T.
- $\Delta\varphi(e^{\pm}, \mu^{\mp})$: the difference in the φ angle between the two leptons of the event.
- $p_Z(e^{\pm}, \mu^{\mp}, j)$: the longitudinal momentum component of the system formed by the muon, the electron, and the jet of the event.
- $m(e^{\pm}, \mu^{\mp}, j)$: the invariant mass of the system formed by the electron, the muon, and the jet.
- $m_T(e^{\pm}, \mu^{\mp}, j, p_T^{miss})$: the transverse mass of the system formed by the electron, the muon, the jet, and the missing transverse energy of the event.

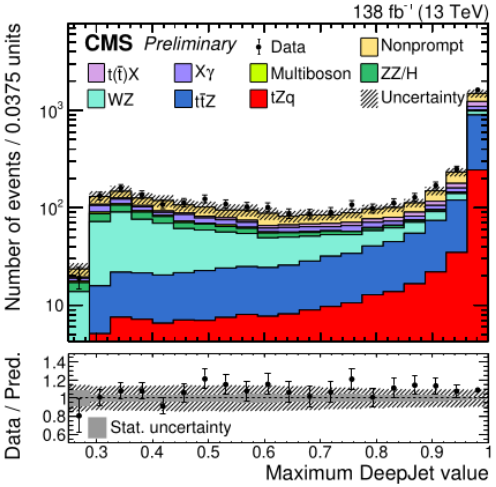

CMS
Preliminary
138 fb^{-1} (13 TeV)
Data
Total unc.
Stat unc.
tW PH DR + P8
tW PH DS + P8
tW PH DR + H7
tW aMC DR + P8
tW aMC DR2 + P8
tW aMC DS + P8
tW aMC DS dyn. + P8
$(1/\sigma_{fid.})d\sigma/d(\text{jet } p_T)$ (1/GeV)
Pred./Data
Jet p_T (GeV)
$(1/\sigma_{fid.})d\sigma/d(m(e^{\pm}, \mu^{\mp}, j))$ (1/GeV)
$m(e^{\pm}, \mu^{\mp}, j)$ (GeV)

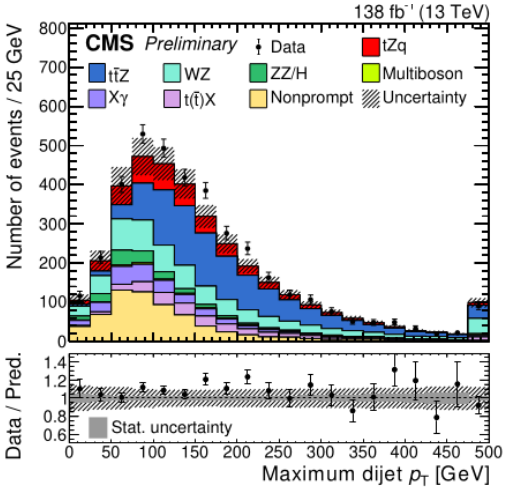

Fit constraint (obs.)
+1σ impact (obs.)
-1σ impact (obs.)
Fit constraint (exp.)
+1σ impact (exp.)
-1σ impact (exp.)
CMS Preliminary
μ = 1.10 +0.11 −0.11
JES - Absolute corr.
Non-W/Z normalisation
tW μR and μF scales
Final-state radiation (tt̄, tW)
VV+tt̄V normalisation
Electron ID eff.
Pileup
Drell-Yan normalisation
MC stat. in bin 20 of 1j1b-BDT
JES - Relative sample (2016)
Luminosity corr. (2016, 2017, 2018)
tt̄ μR and μF scales
JES - Absolute uncorr. (2018)
b-tagging corr.
JES - BBEC1 corr.
JER (2018)
JES - Flavour QCD
Underlying event
Colour rec. (MPI tune with ERD)
tW DR/DS
−2
−1
0
1
2
(θ̂-θ0)/Δθ
−0.05
0
0.05
Δμ̂

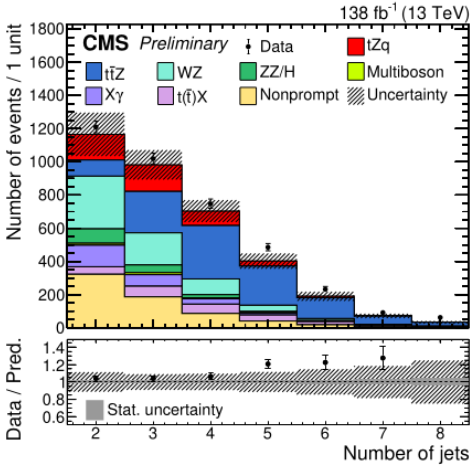


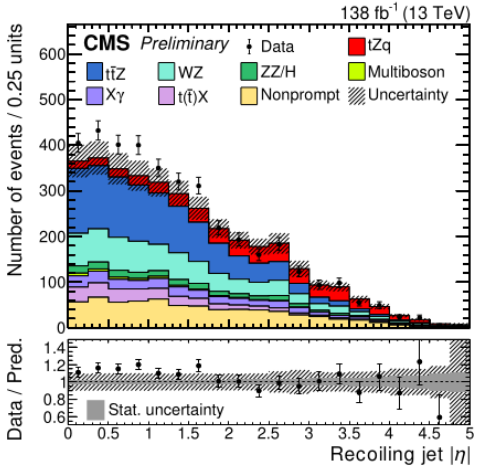


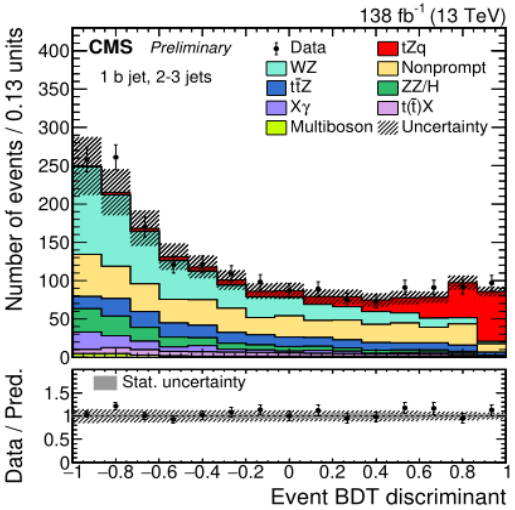
Some input variables

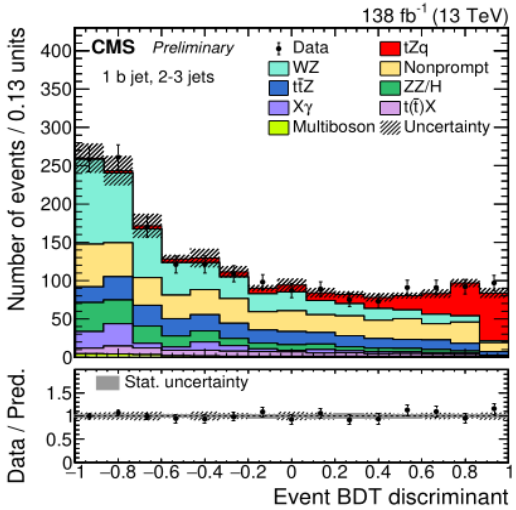




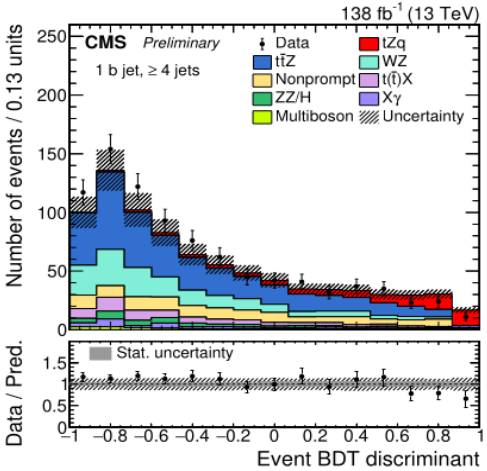


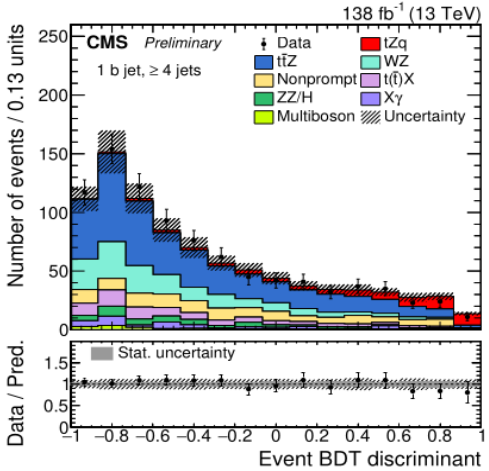


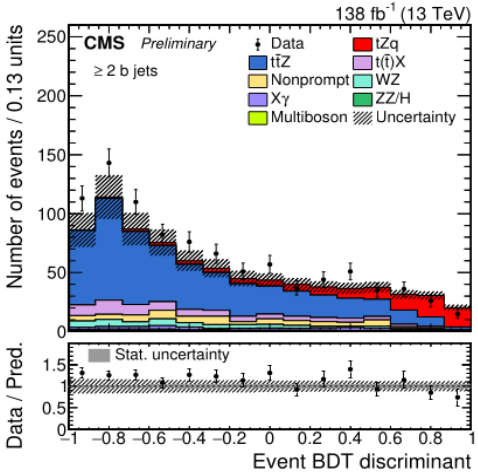


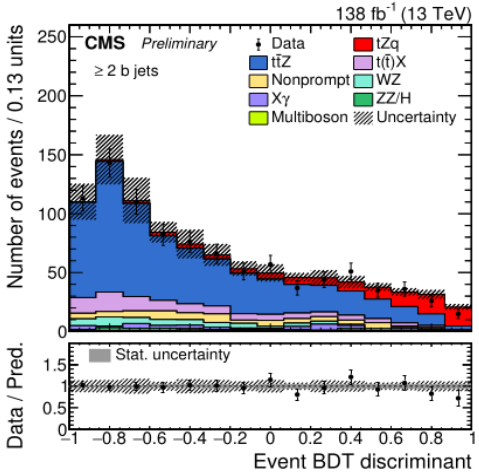


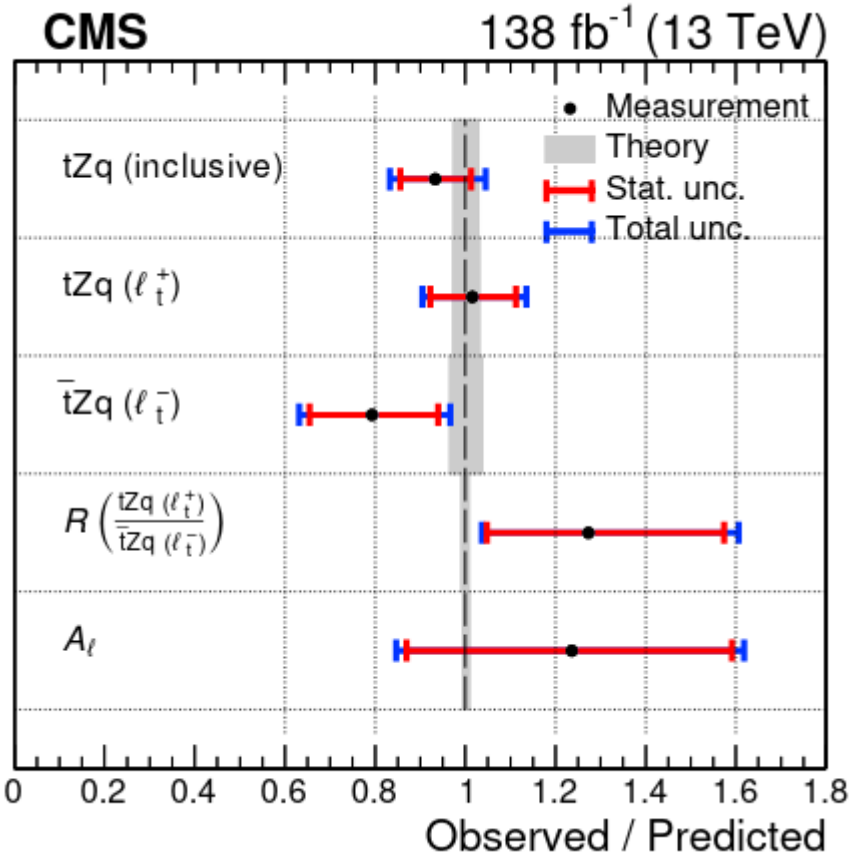
BDT discriminants for all 3 signal regions

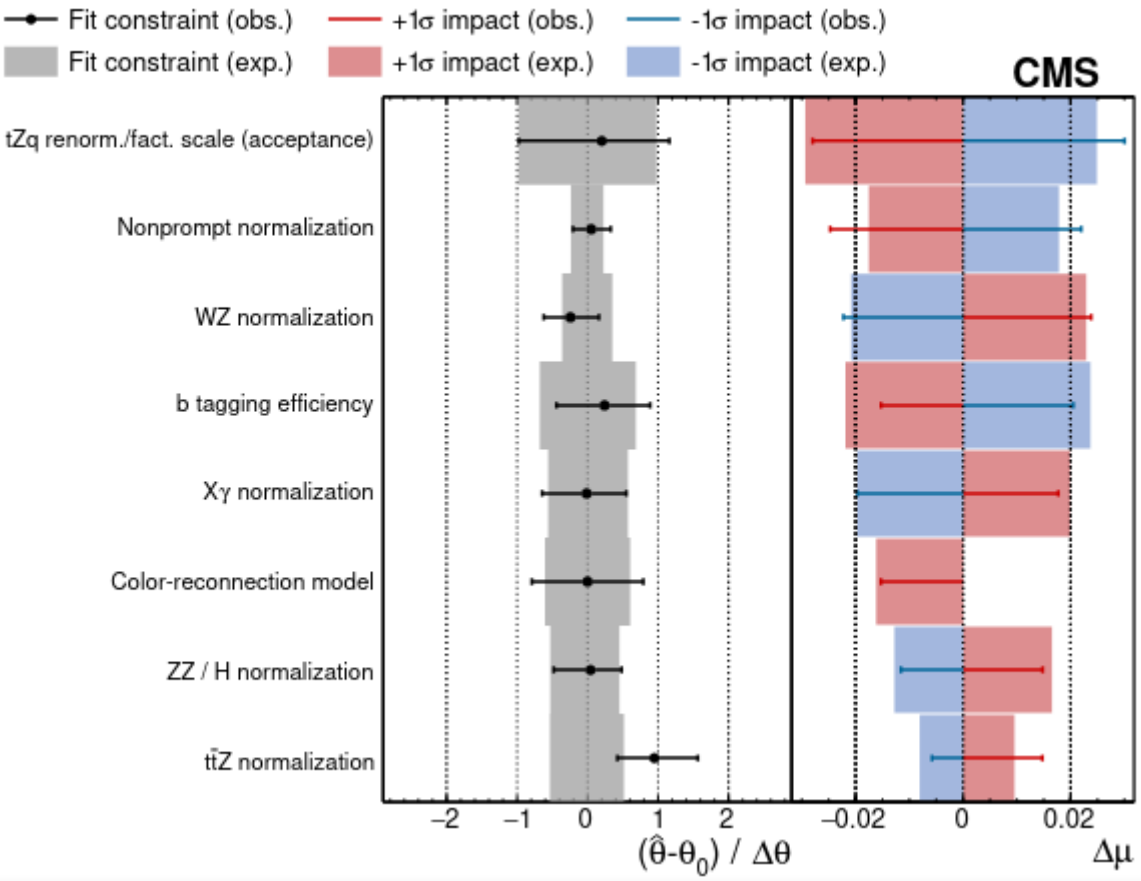


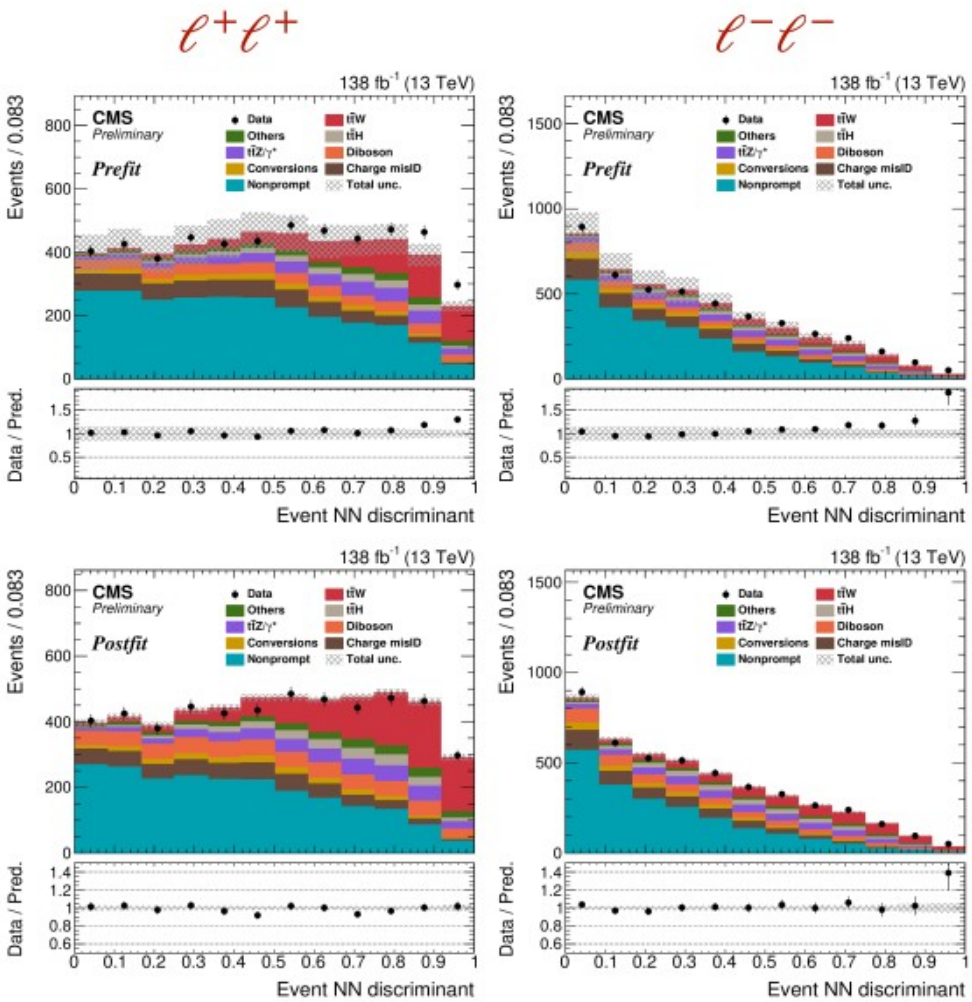


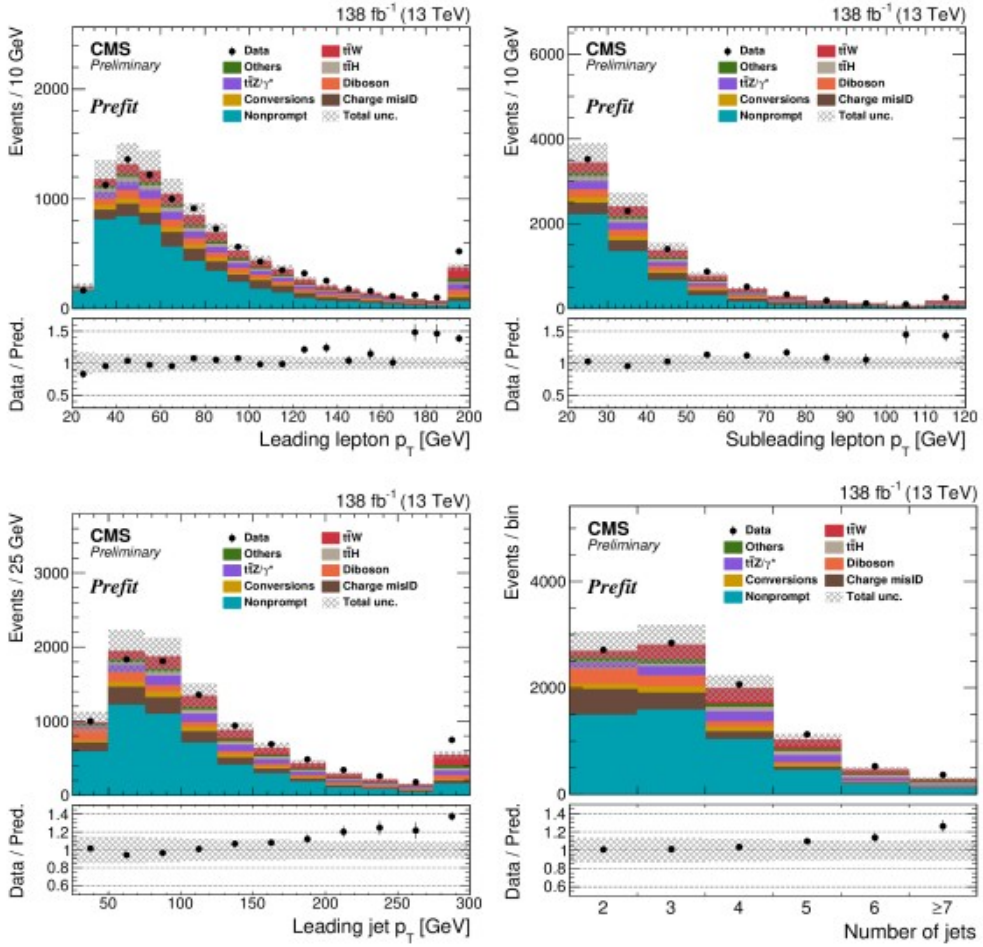




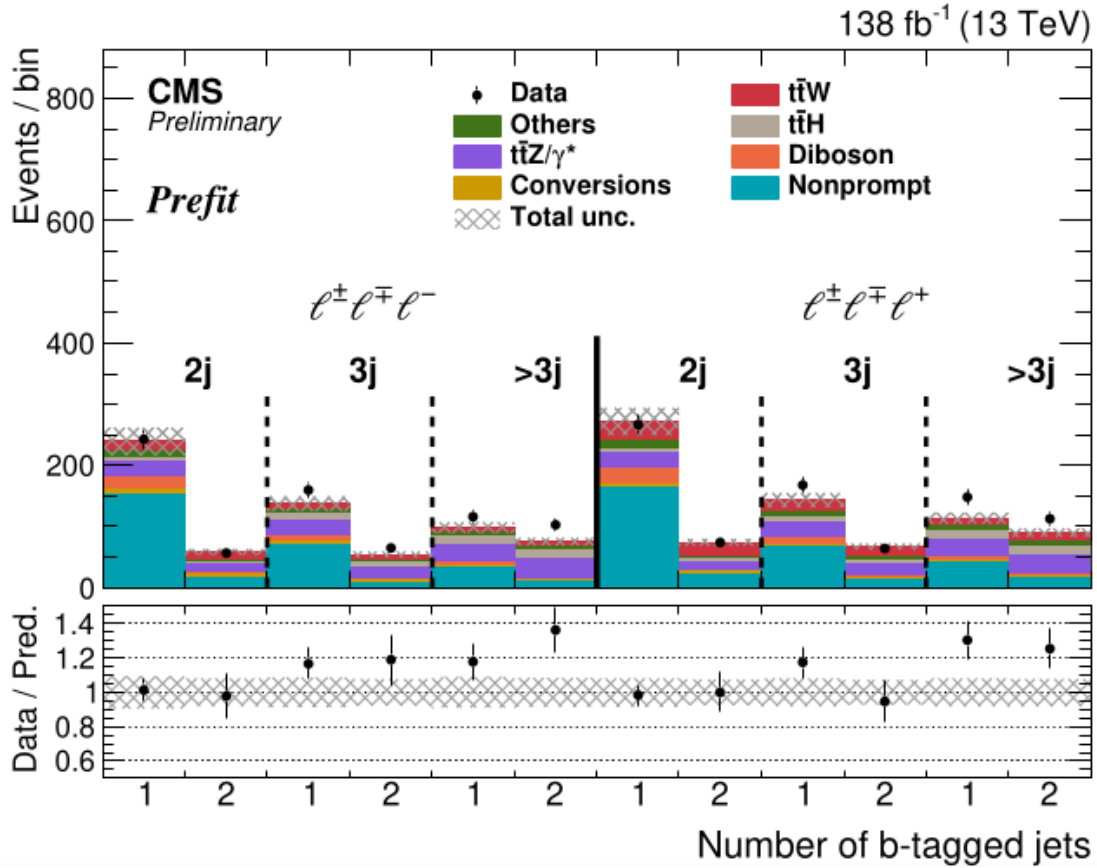

CMS
138 fb-1 (13 TeV)
Measurement
Theory
Stat. unc.
Total unc.
tZq (inclusive)
tZq (ℓ+t)
t̄Zq (ℓ−t)
R (tZq (ℓ+t) / t̄Zq (ℓ−t))
Aℓ
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
Observed / Predicted

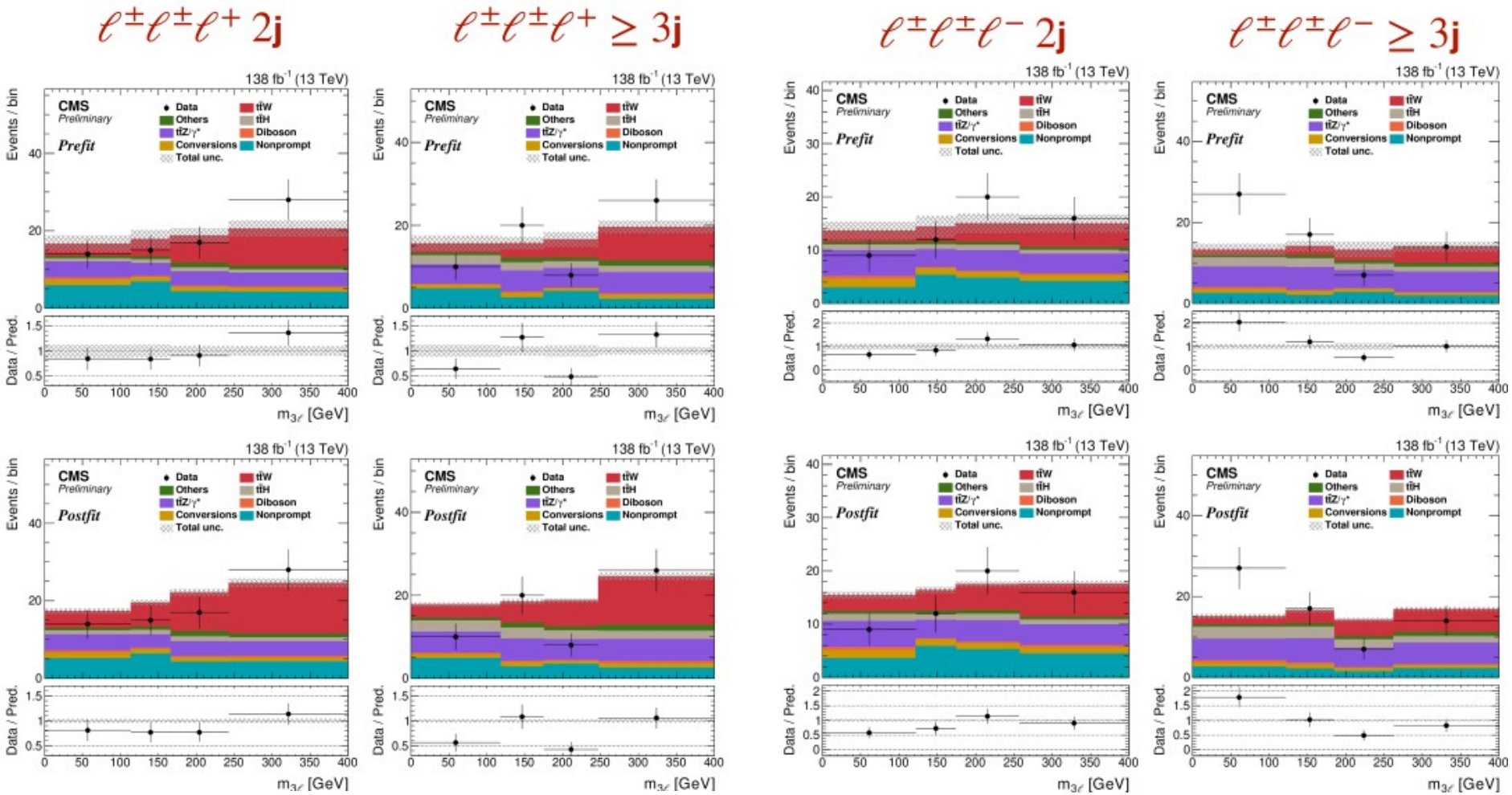

Fit constraint (obs.)
Fit constraint (exp.)
+1σ impact (obs.)
+1σ impact (exp.)
-1σ impact (obs.)
-1σ impact (exp.)
CMS
tZq renorm./fact. scale (acceptance)
Nonprompt normalization
WZ normalization
b tagging efficiency
Xγ normalization
Color-reconnection model
ZZ / H normalization
tt̄Z normalization
−2 −1 0 1 2
(θ̂-θ0) / Δθ
−0.02 0 0.02
Δμ


$\ell^+\ell^+$
$\ell^-\ell^-$
138 fb^{-1} (13 TeV)
CMS
Preliminary
Prefit
Postfit
Data
Others
$t\bar{t}Z/\gamma^*$
Conversions
Nonprompt
$t\bar{t}W$
$t\bar{t}H$
Diboson
Charge misID
Total unc.
Events / 0.083
Data / Pred.
Event NN discriminant

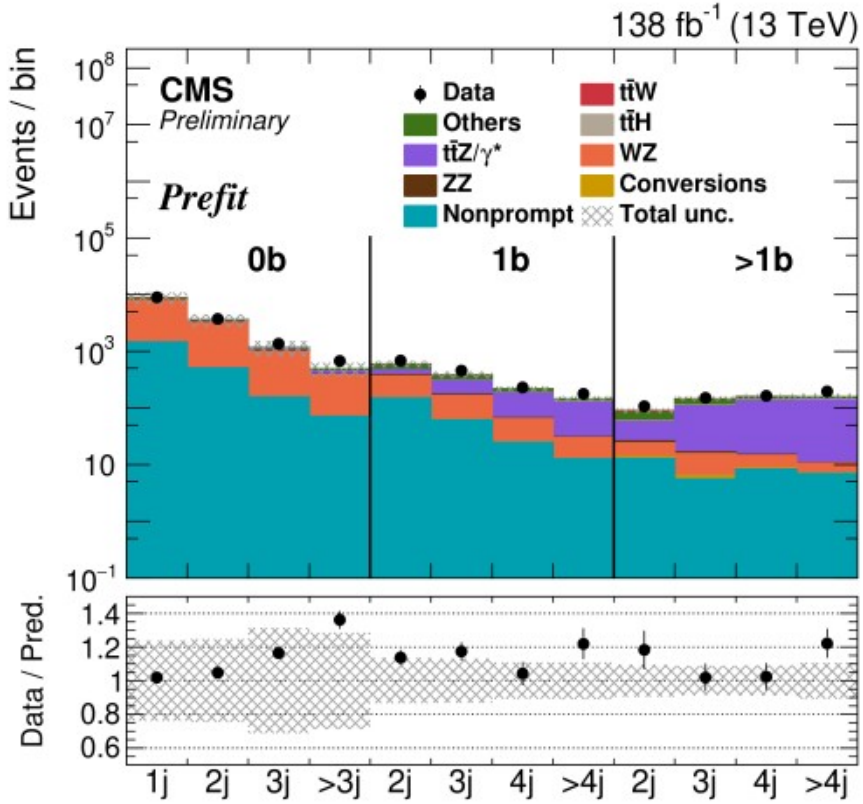

138 fb^{-1} (13 TeV)
CMS
Preliminary
Prefit
Data
Others
$t\bar{t}Z/\gamma^*$
Conversions
Nonprompt
$t\bar{t}W$
$t\bar{t}H$
Diboson
Charge misID
Total unc.
Events / 10 GeV
Events / 25 GeV
Events / bin
Data / Pred.
Leading lepton p_T [GeV]
Subleading lepton p_T [GeV]
Leading jet p_T [GeV]
Number of jets

3-lepton signal region categories

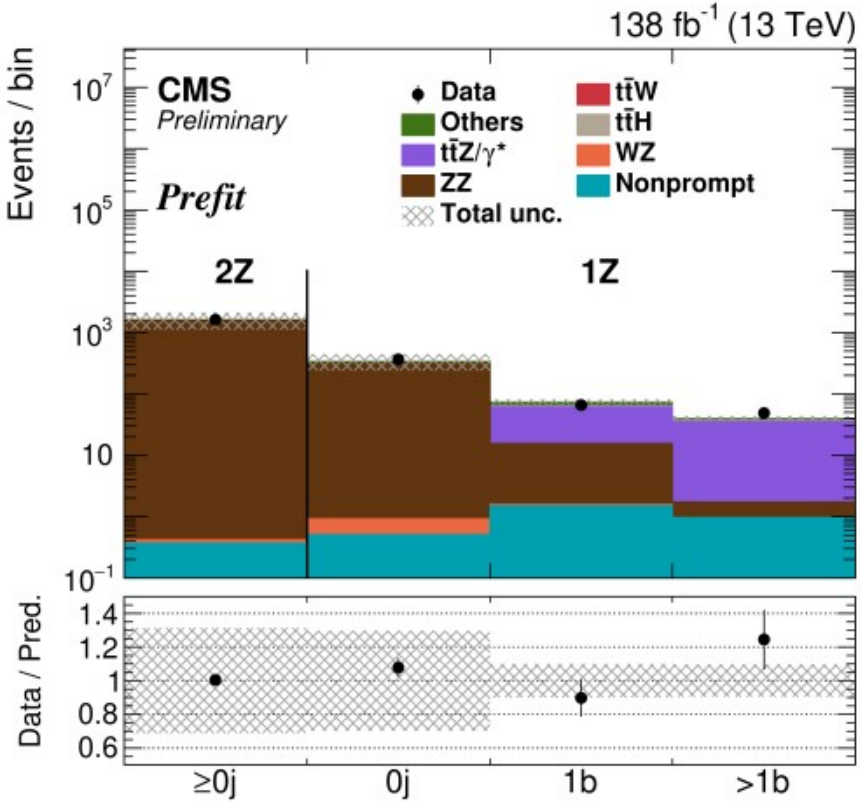



$\ell^{\pm}\ell^{\pm}\ell^{+}$ 2j
$\ell^{\pm}\ell^{\pm}\ell^{+} \geq 3$j
$\ell^{\pm}\ell^{\pm}\ell^{-}$ 2j
$\ell^{\pm}\ell^{\pm}\ell^{-} \geq 3$j
138 fb^{-1} (13 TeV)
CMS
Preliminary
Prefit
Postfit
Data
Others
tt̄Z/γ*
Conversions
Total unc.
tt̄W
tt̄H
Diboson
Nonprompt
Events / bin
Data / Pred.
$m_{3\ell}$ [GeV]

3-lepton control regions



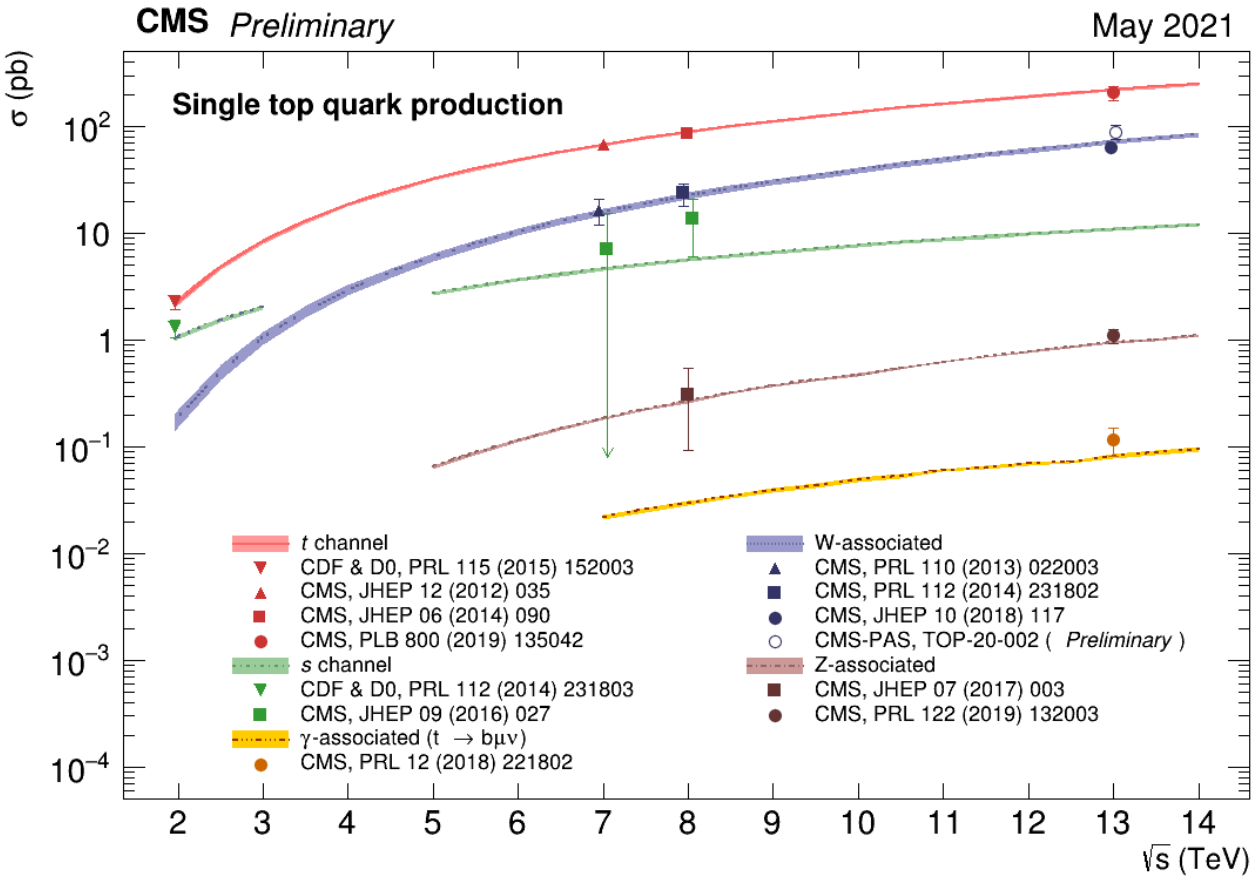
4-lepton control region

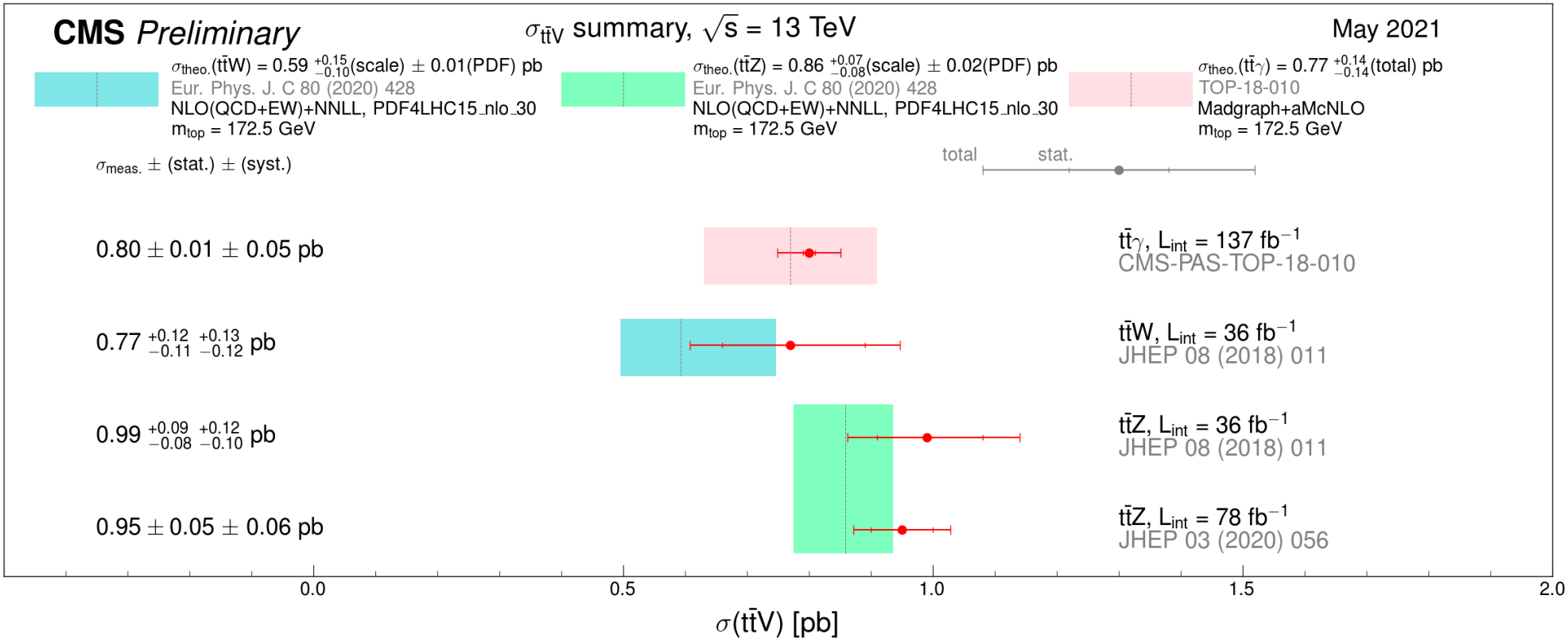


Uncertainty type	Relative value (%)
Experimental	
Integrated luminosity	1.9
Charge misidentification	1.6
bjet identification	1.6
Nonprompt lepton background	1.3
Trigger efficiencies	1.2
Pileup	1.0
Trigger prefiring	0.7
Jet energy scale	0.6
Jet energy resolution	0.4
Lepton efficiencies	0.4
Normalizations	
$t\bar{t}H$	2.6
VVV	1.2
$t\bar{t}VV$	1.2
Conversions	0.7
$t\bar{t}\gamma$	0.6
ZZ	0.6
Others	0.5
$t\bar{t}Z$	0.3
WZ	0.2
tZq	0.2
tHq	0.2
Modelling	
$t\bar{t}W$ scale	1.8
$t\bar{t}W$ colour reconnection	1.0
ISR/FSR for $t\bar{t}W$	0.8
$t\bar{t}\gamma$ scale	0.4
VVV scale	0.3
$t\bar{t}H$ scale	0.2
Conversions	0.2
Statistical uncertainty	1.8

Table 1: Number of predicted and observed events in the signal regions after the dileptonic and trileptonic selections. The last column shows the ratio between the number of predicted events after and before the fit. The total uncertainty in the number of predicted events is shown. The symbol "—" indicates that the corresponding background does not apply.

Process	$\ell^+\ell^+$	$\ell^-\ell^-$	$\ell^\pm\ell^\mp\ell^+$	$\ell^\pm\ell^\mp\ell^-$	Postfit/Prefit
$t\bar{t}W$	677 ± 21	355 ± 12	119 ± 9	65 ± 5	1.49
Nonprompt	2486 ± 598	2364 ± 570	325 ± 75	298 ± 71	0.91
Charge misID	521 ± 110	523 ± 111	—	—	0.91
$t\bar{t}H$	167 ± 34	169 ± 34	56 ± 12	57 ± 12	1.35
$t\bar{t}Z/\gamma^*$	335 ± 26	333 ± 26	145 ± 13	147 ± 13	1.10
Diboson	382 ± 88	285 ± 65	47 ± 9	38 ± 8	1.07
Others	178 ± 34	126 ± 27	43 ± 8	34 ± 7	1.20
Conversions	177 ± 54	192 ± 59	23 ± 7	24 ± 7	1.01
Total backgrounds	4246 ± 621	3993 ± 591	639 ± 80	597 ± 76	1.03
Total prediction	4922 ± 623	4348 ± 591	758 ± 81	663 ± 76	1.05
Data	5143	4486	834	744	


CMS Preliminary
May 2021
Single top quark production
σ (pb)
√s (TeV)
t channel
CDF & D0, PRL 115 (2015) 152003
CMS, JHEP 12 (2012) 035
CMS, JHEP 06 (2014) 090
CMS, PLB 800 (2019) 135042
s channel
CDF & D0, PRL 112 (2014) 231803
CMS, JHEP 09 (2016) 027
γ-associated (t → bμν)
CMS, PRL 12 (2018) 221802
W-associated
CMS, PRL 110 (2013) 022003
CMS, PRL 112 (2014) 231802
CMS, JHEP 10 (2018) 117
CMS-PAS, TOP-20-002 (Preliminary)
Z-associated
CMS, JHEP 07 (2017) 003
CMS, PRL 122 (2019) 132003


CMS Preliminary
$\sigma_{t\bar{t}V}$ summary, $\sqrt{s}$ = 13 TeV
May 2021
$\sigma_{theo.}(t\bar{t}W) = 0.59\ ^{+0.15}_{-0.10}$(scale) $\pm$ 0.01(PDF) pb
Eur. Phys. J. C 80 (2020) 428
NLO(QCD+EW)+NNLL, PDF4LHC15_nlo_30
m_{top} = 172.5 GeV
$\sigma_{theo.}(t\bar{t}Z) = 0.86\ ^{+0.07}_{-0.08}$(scale) $\pm$ 0.02(PDF) pb
Eur. Phys. J. C 80 (2020) 428
NLO(QCD+EW)+NNLL, PDF4LHC15_nlo_30
m_{top} = 172.5 GeV
$\sigma_{theo.}(t\bar{t}\gamma) = 0.77\ ^{+0.14}_{-0.14}$(total) pb
TOP-18-010
Madgraph+aMcNLO
m_{top} = 172.5 GeV
$\sigma_{meas.} \pm$ (stat.) $\pm$ (syst.)
total
stat.
0.80 $\pm$ 0.01 $\pm$ 0.05 pb
$t\bar{t}\gamma$, L_{int} = 137 fb^{-1}
CMS-PAS-TOP-18-010
0.77 $^{+0.12}_{-0.11}\ ^{+0.13}_{-0.12}$ pb
$t\bar{t}W$, L_{int} = 36 fb^{-1}
JHEP 08 (2018) 011
0.99 $^{+0.09}_{-0.08}\ ^{+0.12}_{-0.10}$ pb
$t\bar{t}Z$, L_{int} = 36 fb^{-1}
JHEP 08 (2018) 011
0.95 $\pm$ 0.05 $\pm$ 0.06 pb
$t\bar{t}Z$, L_{int} = 78 fb^{-1}
JHEP 03 (2020) 056
0.0
0.5
1.0
1.5
2.0
$\sigma(t\bar{t}V)$ [pb]