

Most recent $t\bar{t}V$ measurements at the LHC

Standard Model at LHC 2022

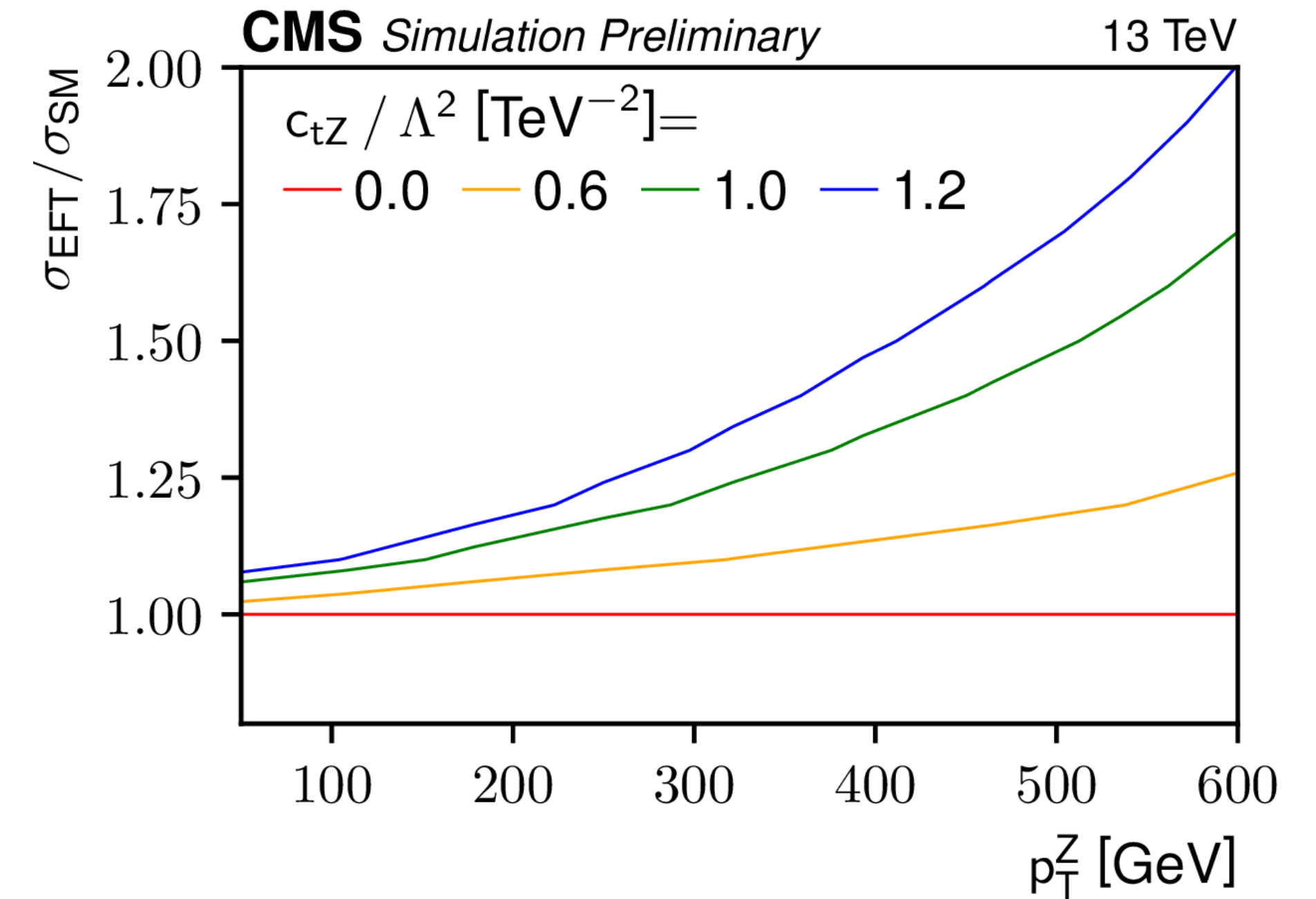
Tu Thong Tran (Catholic University of Louvain and Ghent University)
on behalf of ATLAS and CMS Collaborations

CERN, 12th April 2022

Introduction

- $t\bar{t}V = t\bar{t}W, t\bar{t}Z$ or $t\bar{t}\gamma$
- Probe into top-EWK couplings at tree level, any deviation from the SM can signal new physics
- Highly sensitive to several EFT operators
- Important irreducible backgrounds of many LHC searches (especially in multilepton final states)

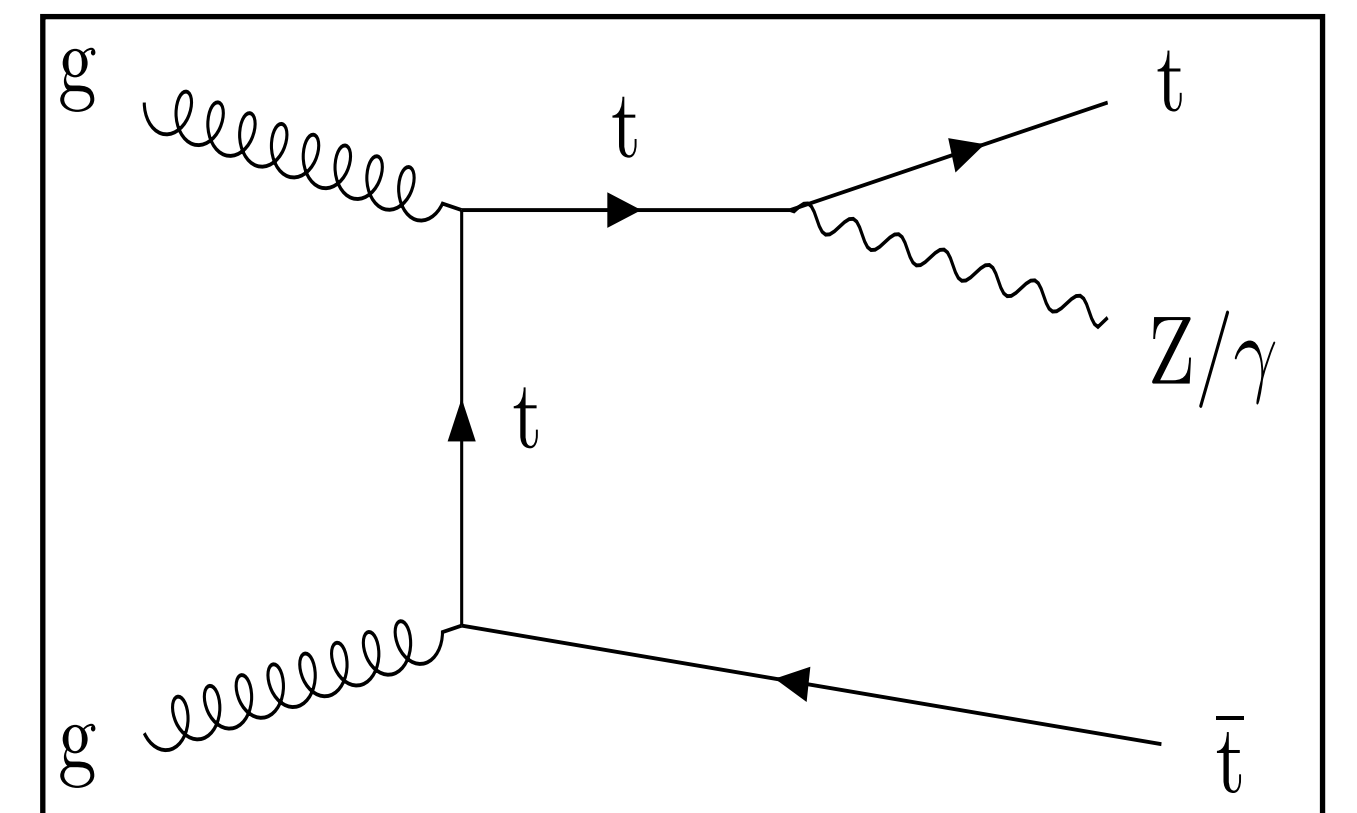
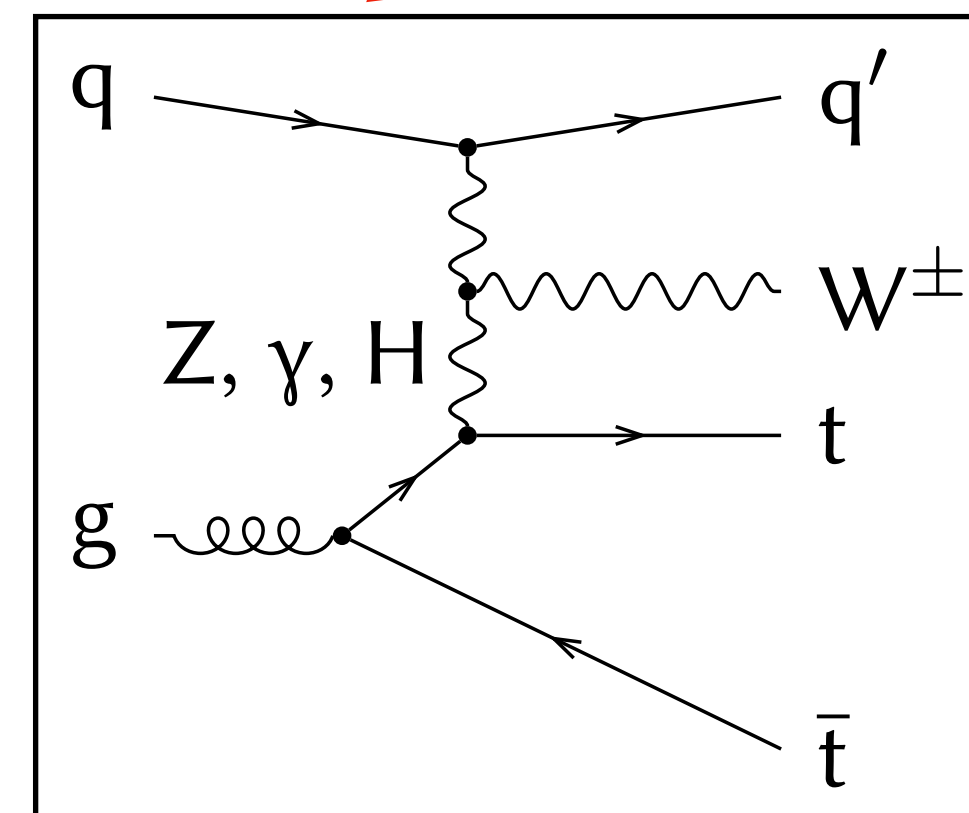
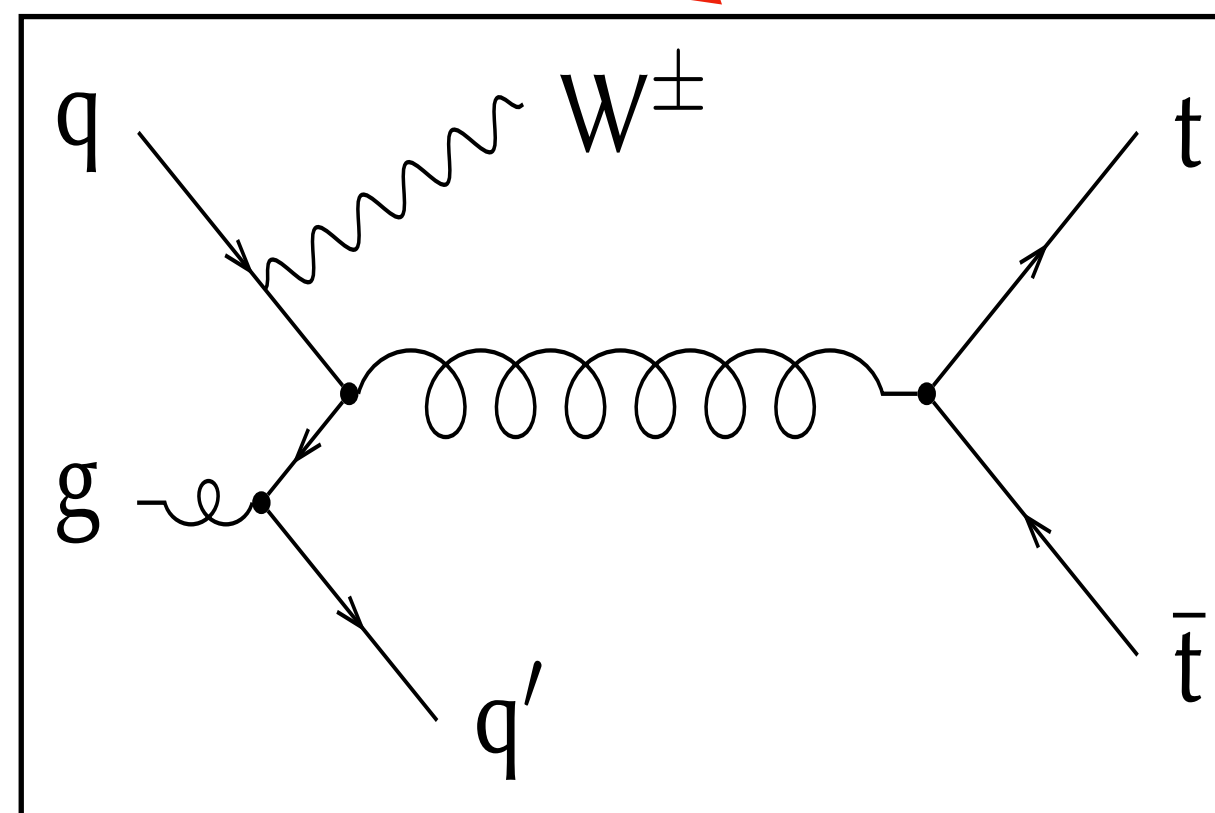
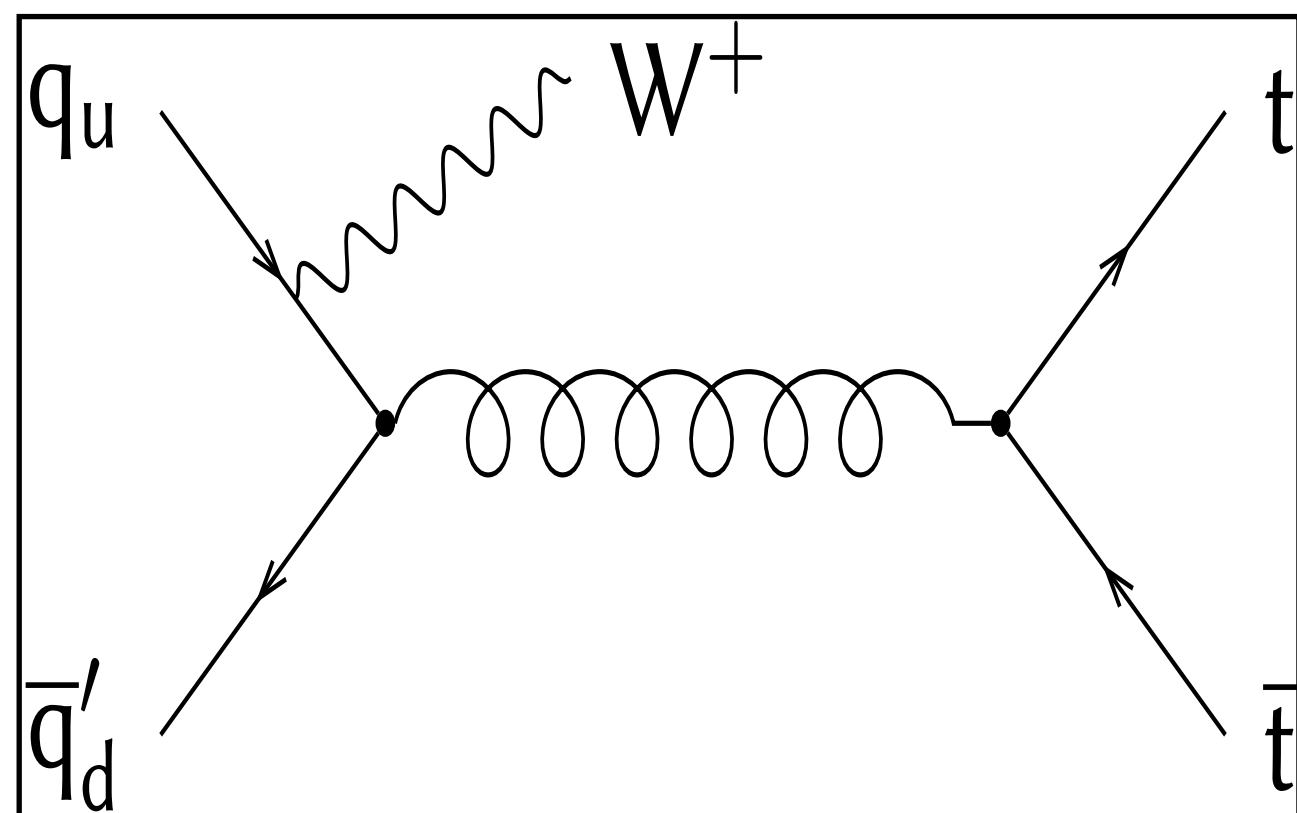
[CMS-PAS-TOP-21-003]



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

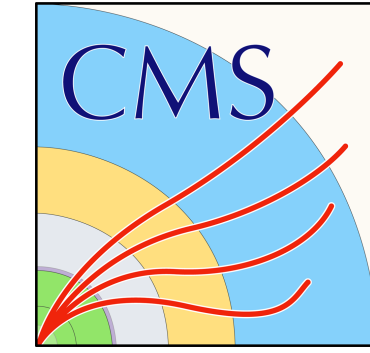
$t\bar{t}W$ (NLO)

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

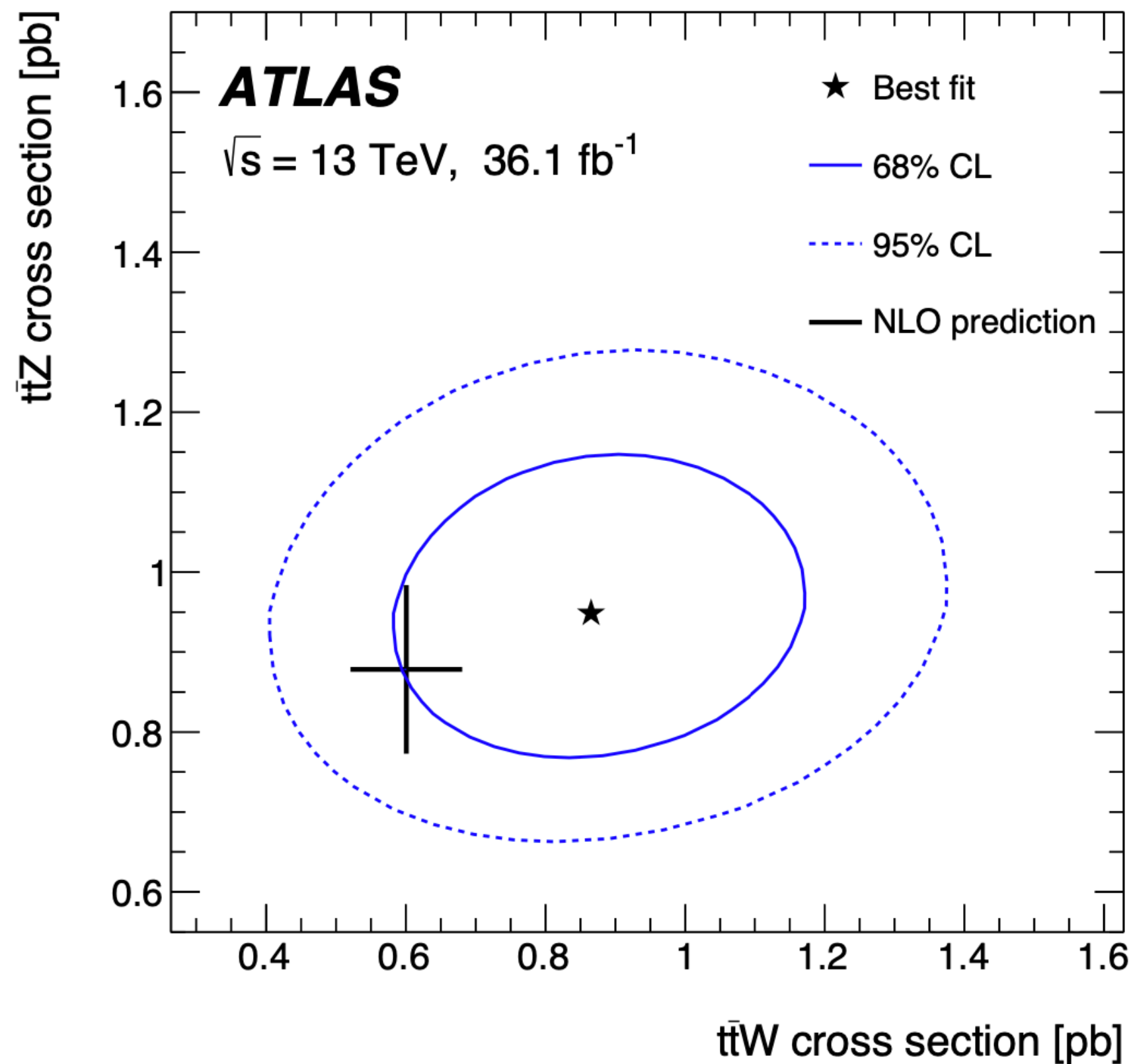


$t\bar{t}W$ measurements

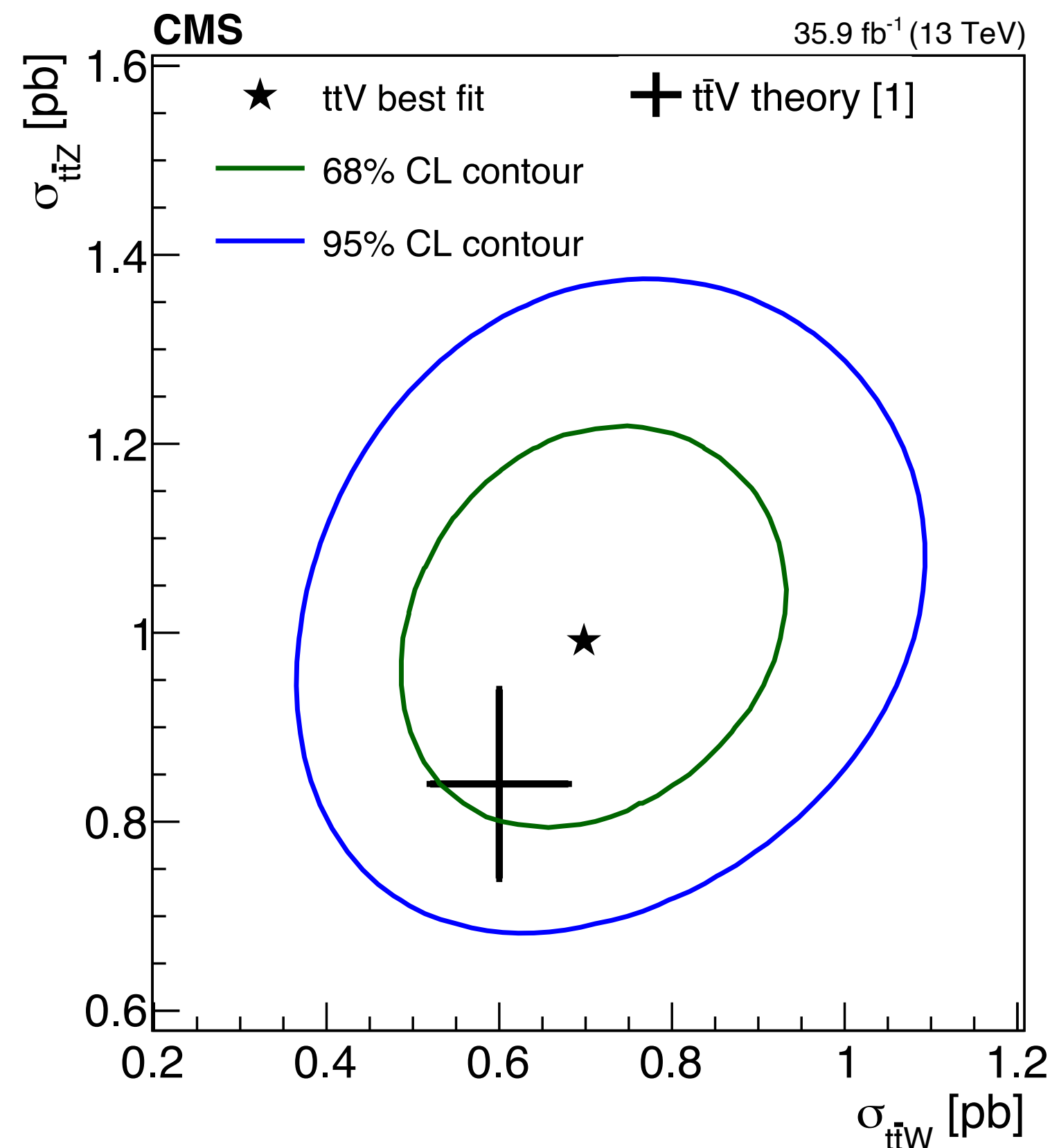
Inclusive cross-section



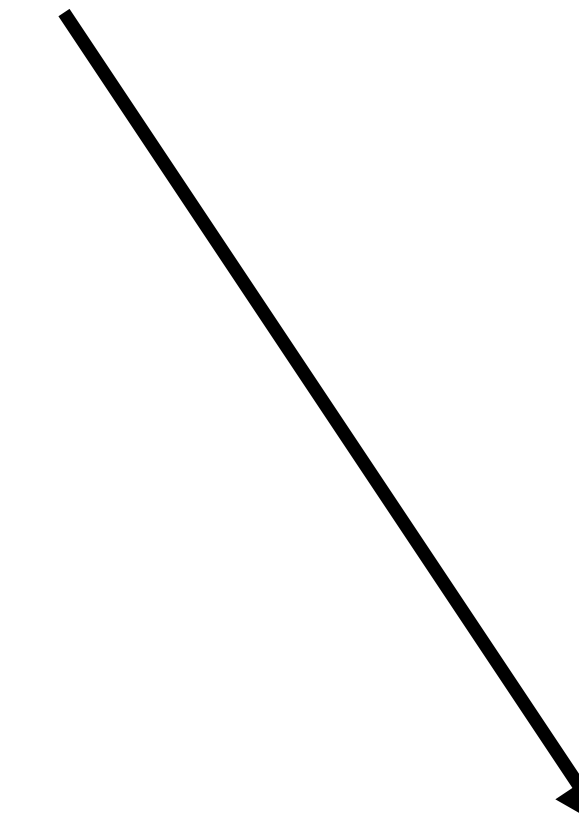
- Previously measured by both ATLAS ([PRD 99 \(2019\) 072009](#)) and CMS ([JHEP 08 \(2018\) 011](#)) with 36 fb⁻¹ data
- Observations were higher than predictions



$$\sigma(t\bar{t}W) = 0.87 \pm 0.13 \text{ (stat)} \pm 0.14 \text{ (syst) pb}$$



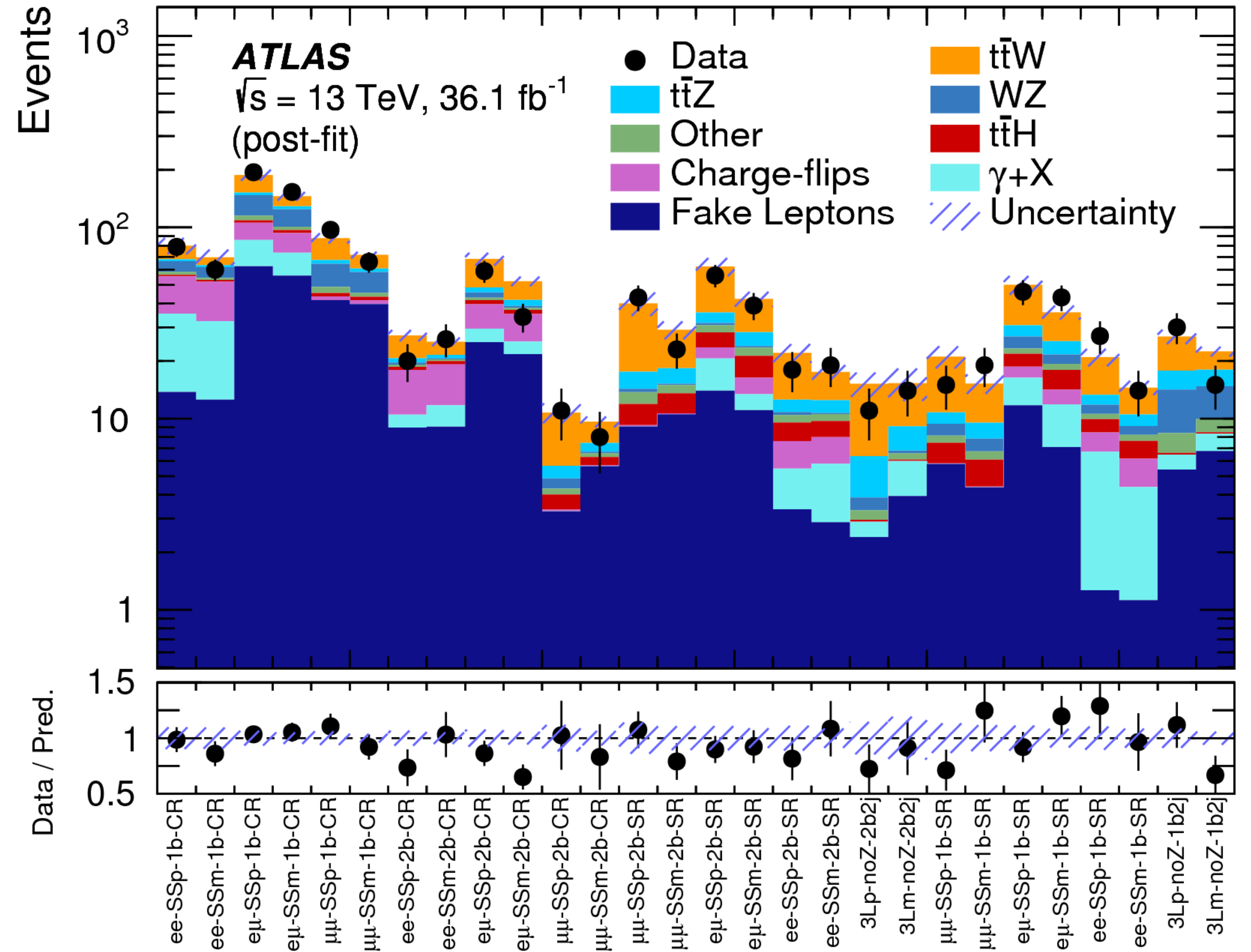
$$\sigma(t\bar{t}W) = 0.77^{+0.12}_{-0.11} \text{ (stat)} \text{ }^{+0.13}_{-0.12} \text{ (syst) pb}$$



New $t\bar{t}W$ inclusive cross section result recently released by CMS

$t\bar{t}W$ measurements

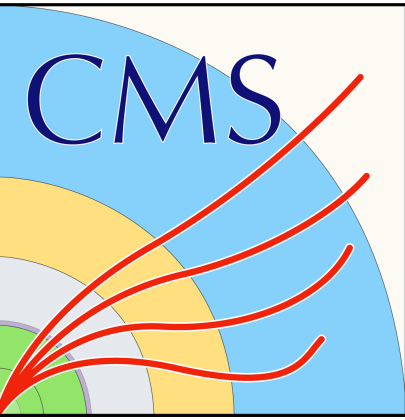
- Signature: 2 same-sign and 3 leptons
- Categories: jet and b jet multiplicities, charge and flavour of lepton pairs
- Simultaneous fit with $t\bar{t}Z$
- $\sigma(t\bar{t}W) = 0.87 \pm 0.13$ (stat) ± 0.14 (syst) pb
- Leading uncertainties:
 - $t\bar{t}W$ modelling (8.5%)
 - Data-driven background statistic (6.3%)
 - Fake leptons and charge misID (5.7%)



$t\bar{t}W$ measurements

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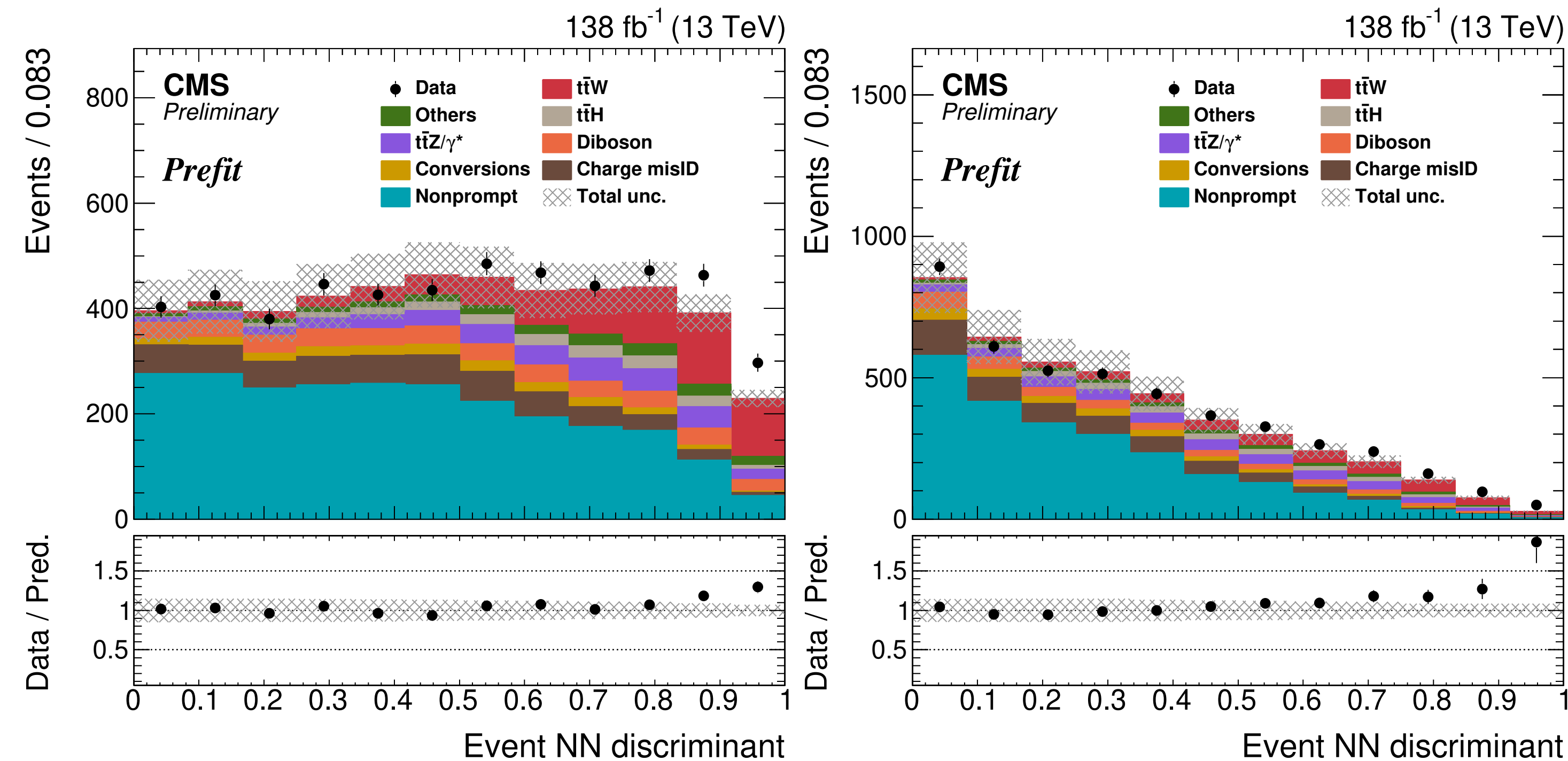


- Signature: same-sign dilepton and 3-lepton
- Categories: lepton flavours and charge (in 2SSL); and jet and b jet multiplicities, and sum of lepton charge (3-lepton)
- Multi-node neural network used in event categorisation in 2SSL (4 nodes: $t\bar{t}W$, $t\bar{t}H/Z$, $t\bar{t}\gamma^*$ and nonprompt leptons)
- Binned profile likelihood fit to NN (in 2SSL) and $m(3\ell)$ (in 3l) distributions (simultaneously)

2SSL final states

$\ell^+\ell^+$

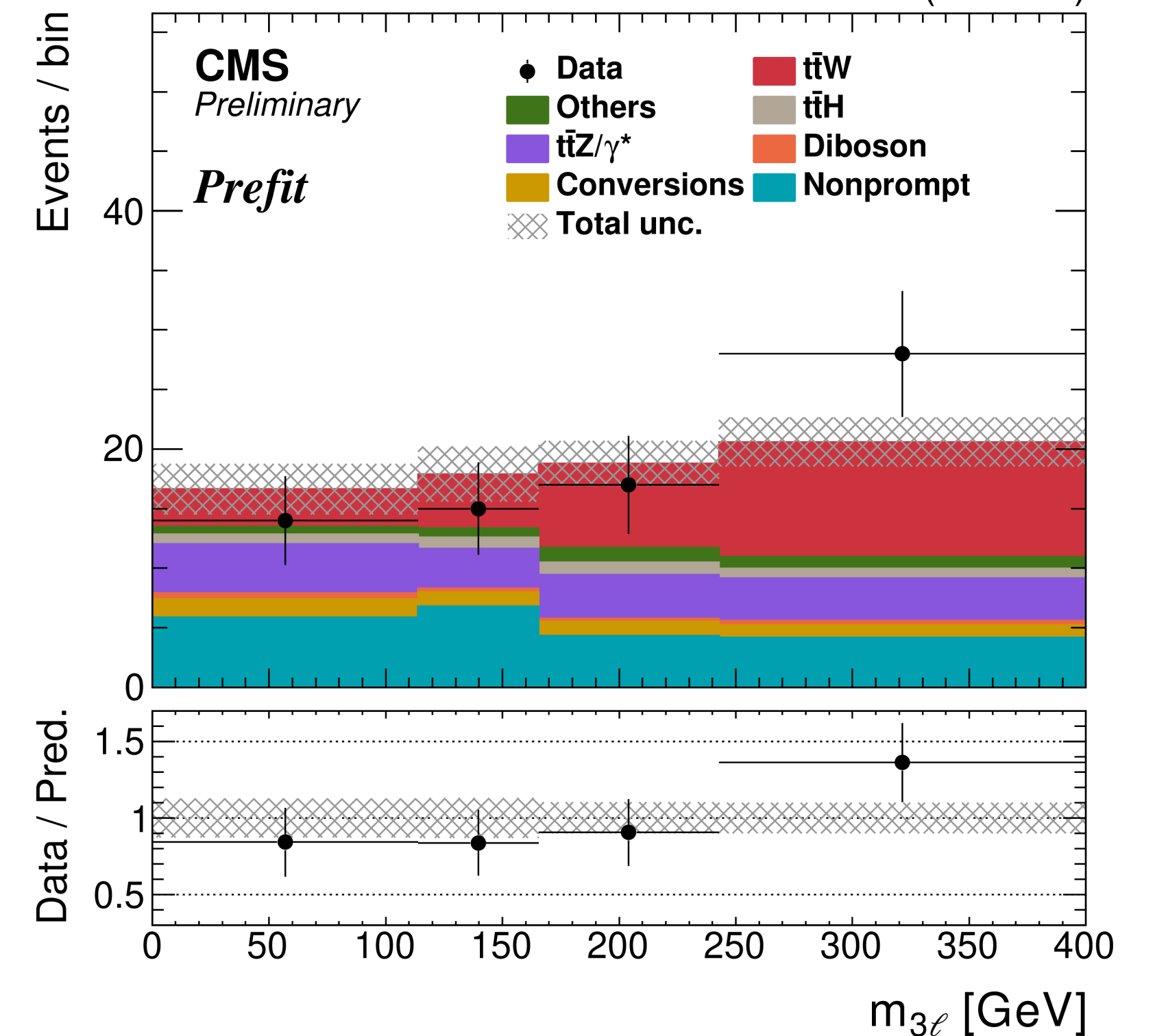
$\ell^-\ell^-$



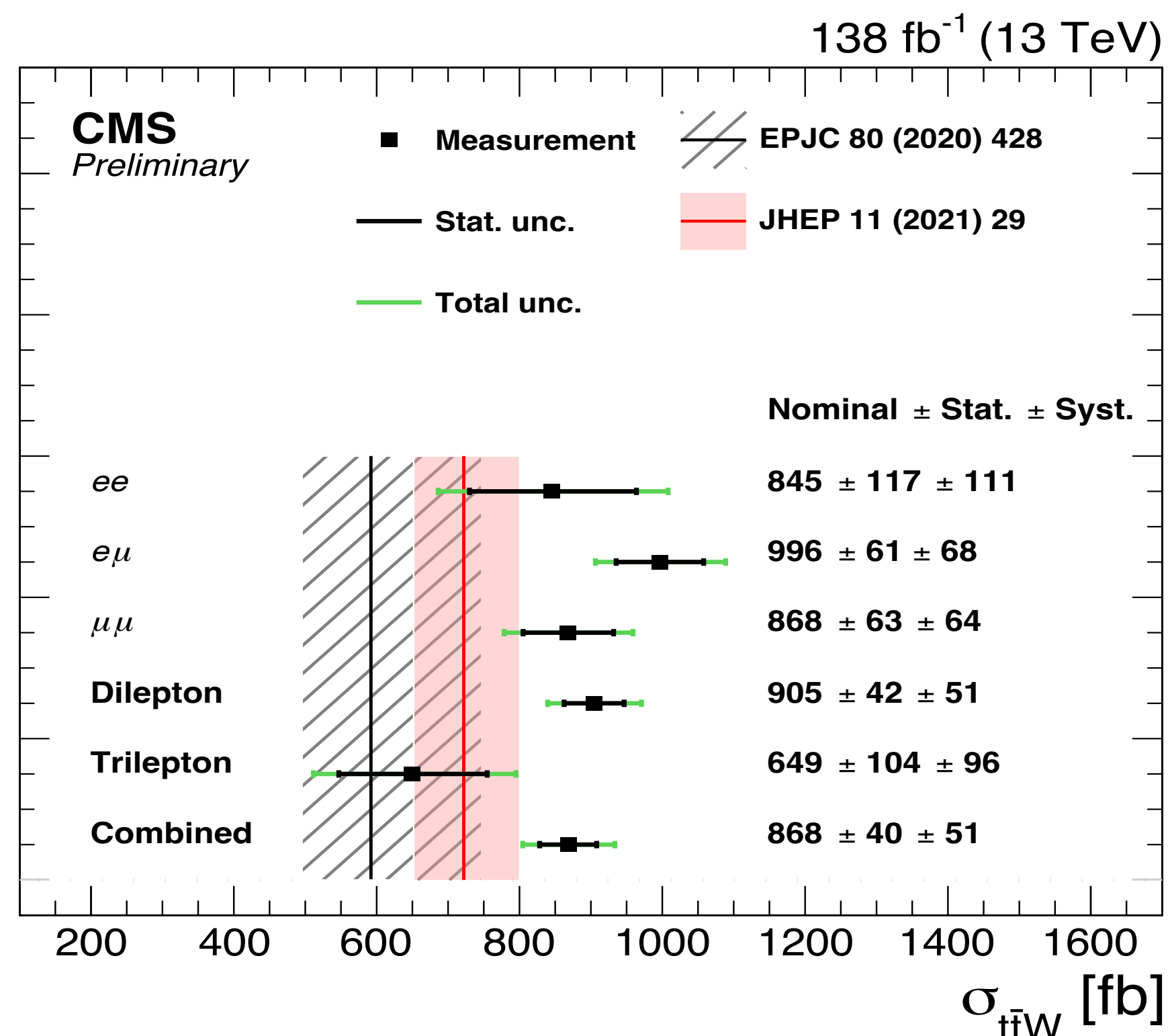
3-lepton final states

$\ell^\pm\ell^\mp\ell^+$, 2j 2b

138 fb⁻¹ (13 TeV)



Theoretical prediction of inclusive cross section at NLO+NNLL [[EPJC 80 \(2020\) 428, A. Kulesza et al.](#)] and NLO+FxFx@2J [[JHEP 11 \(2021\) 029, R. Frederix, I. Tsinikos](#)] with improved FxTx merging



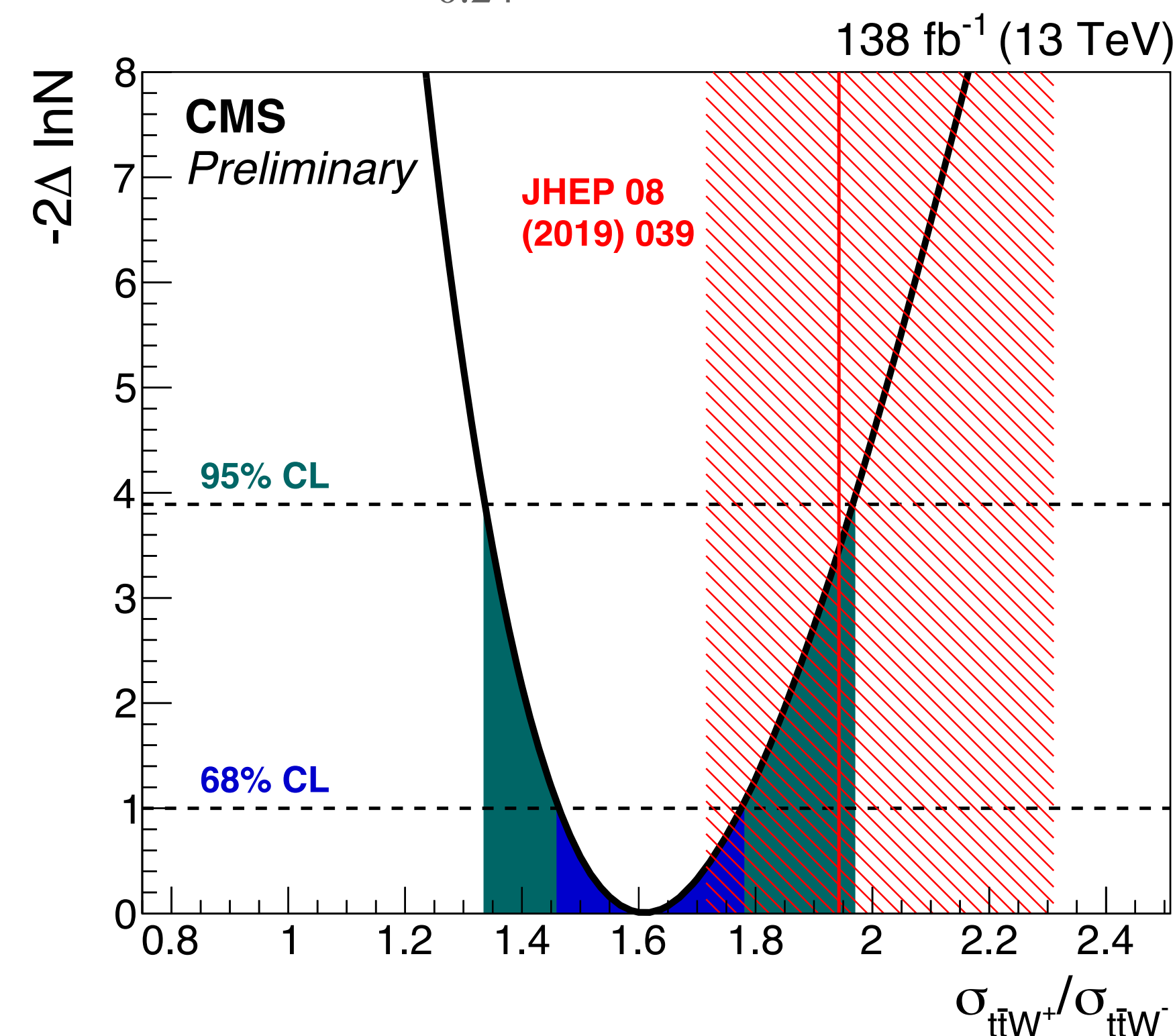
Ratio of $\sigma(t\bar{t}W^+)/\sigma(t\bar{t}W^-)$

Measurement:

$$R_{t\bar{t}W^+/t\bar{t}W^-} = 1.61^{+0.15}_{-0.14}(\text{stat})^{+0.07}_{-0.05}(\text{syst})$$

Prediction NLO+NNLL [[JHEP 08 \(2019\) 039, A. Broggio et al.](#)]:

$$R_{t\bar{t}W^+/t\bar{t}W^-} = 1.94^{+0.37}_{-0.24}$$



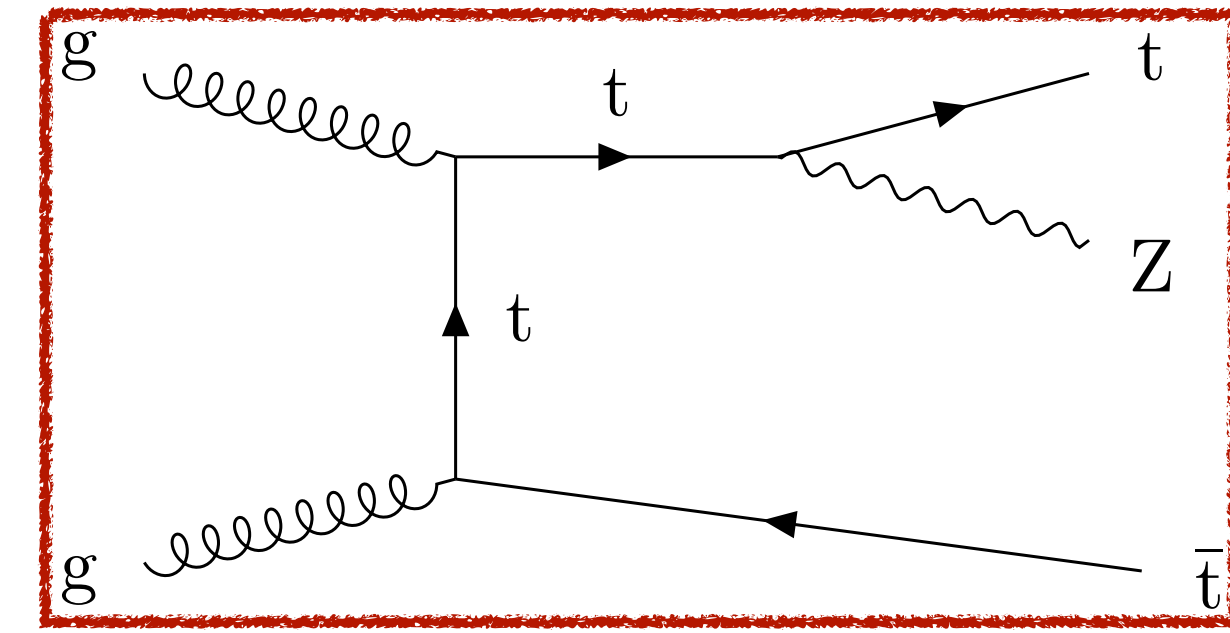
- Compared to previous CMS measurement: reduced both stat. and syst. by more than half
- Leading uncertainties:
 - $t\bar{t}H$ normalisation (2.6%)
 - Integrated luminosity (1.9%)
 - $t\bar{t}W$ scale (1.8%)

$t\bar{t}Z$ measurements

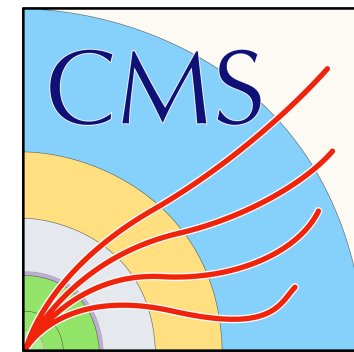
Inclusive and differential cross-sections

- The most sensitive process to t-Z coupling
- Latest measurements from both ATLAS ([EPJC 81 \(2021\) 737](#)) and CMS ([JHEP 03 \(2020\) 056](#)) are in good agreement with theoretical prediction:

$$0.86^{+0.07}_{-0.08}(\text{scale}) \pm 0.03(\text{PDF}) \text{ pb} - [\text{Kulesza et al. (EPJC 79 (2019) 249)}]$$



$\sigma(t\bar{t}Z) = 0.95 \pm 0.05(\text{stat}) \pm 0.06(\text{syst}) \text{ pb}$
with data 2016-2017 data (77 fb⁻¹)



- Leading uncertainties:
 - Lepton-ID efficiency (4%)
 - WZ cross section (3%)
 - Integrated luminosity, trigger, jet energy scale and $t(\bar{t})X$ backgrounds (2%)

$\sigma(t\bar{t}Z) = 0.99 \pm 0.05(\text{stat}) \pm 0.08(\text{syst}) \text{ pb}$
with full Run-2 data (139 fb⁻¹)



- Leading uncertainties:
 - $t\bar{t}Z$ parton shower (3.1%)
 - tWZ modelling and b-tagging (2.9%)
 - $WZ/ZZ +$ jet modelling (2.8%)

$t\bar{t}Z$ measurements

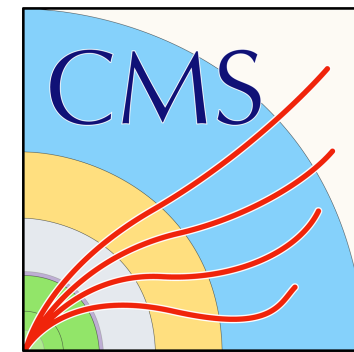
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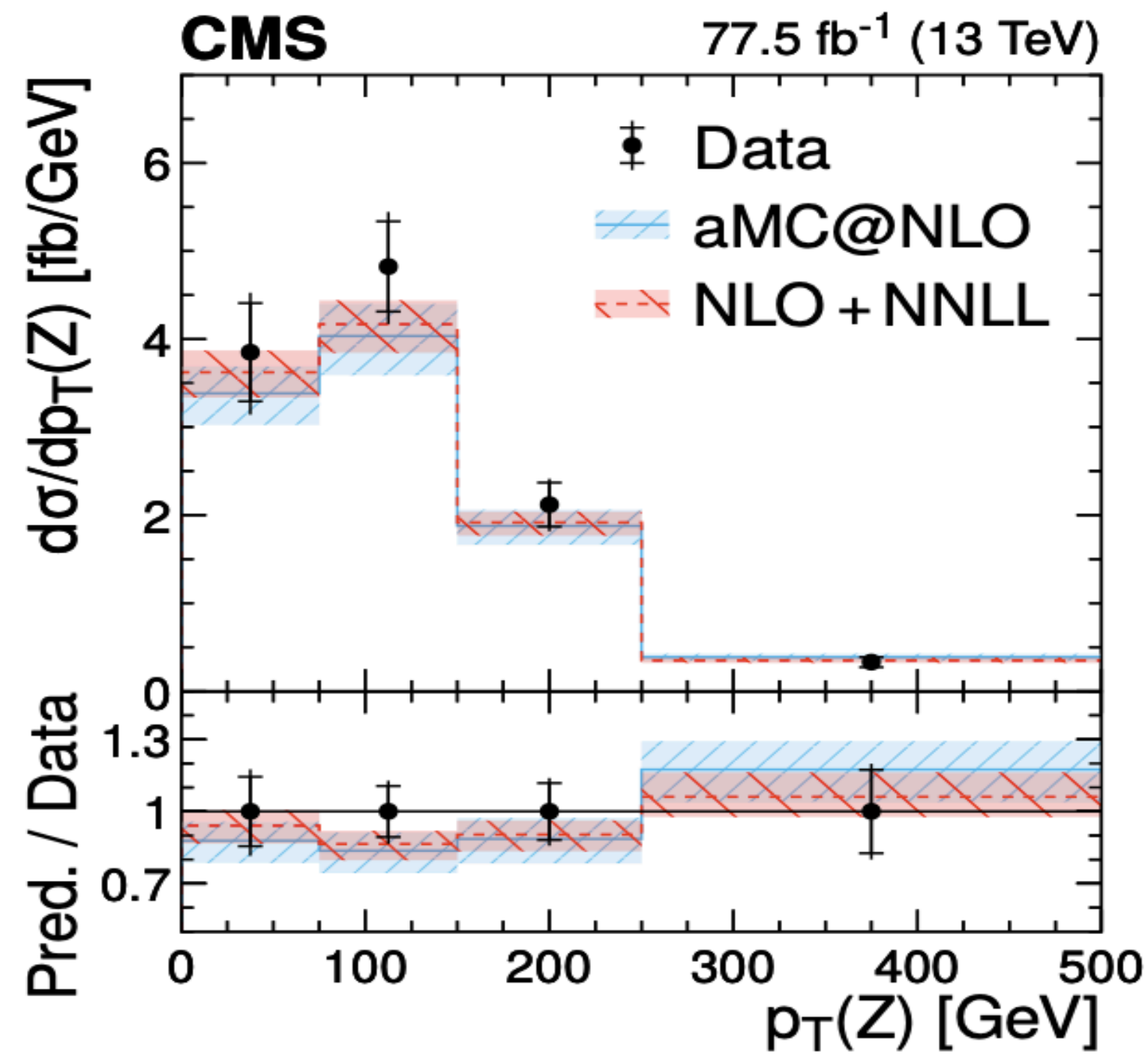
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with data 2016-2017 data (77 fb⁻¹)

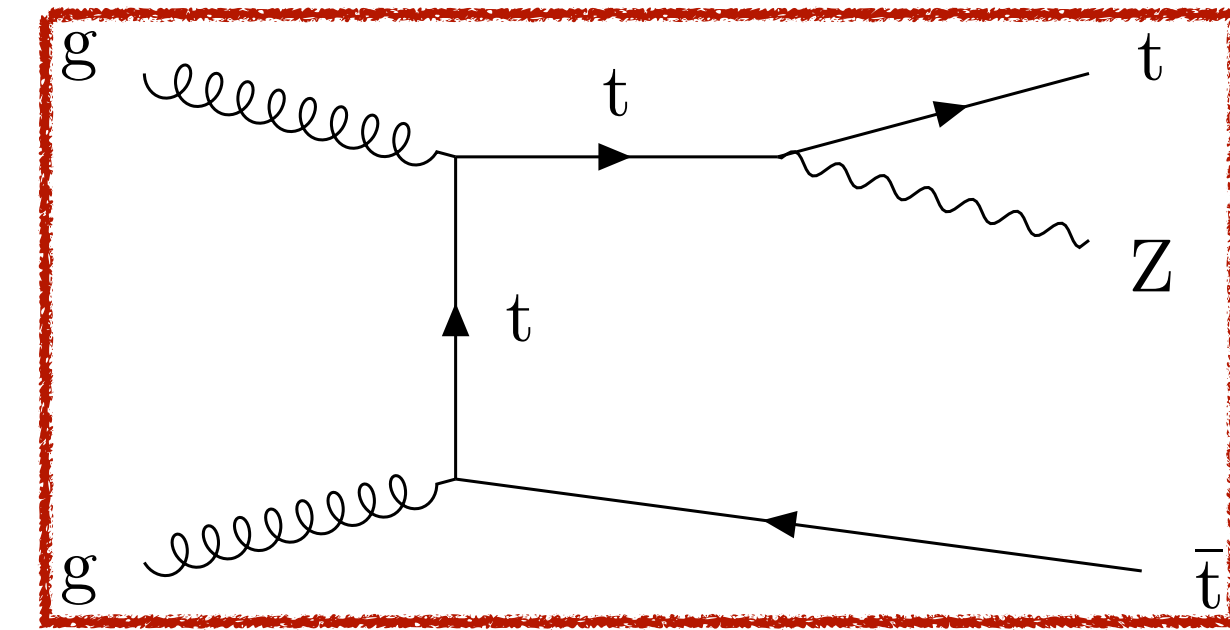
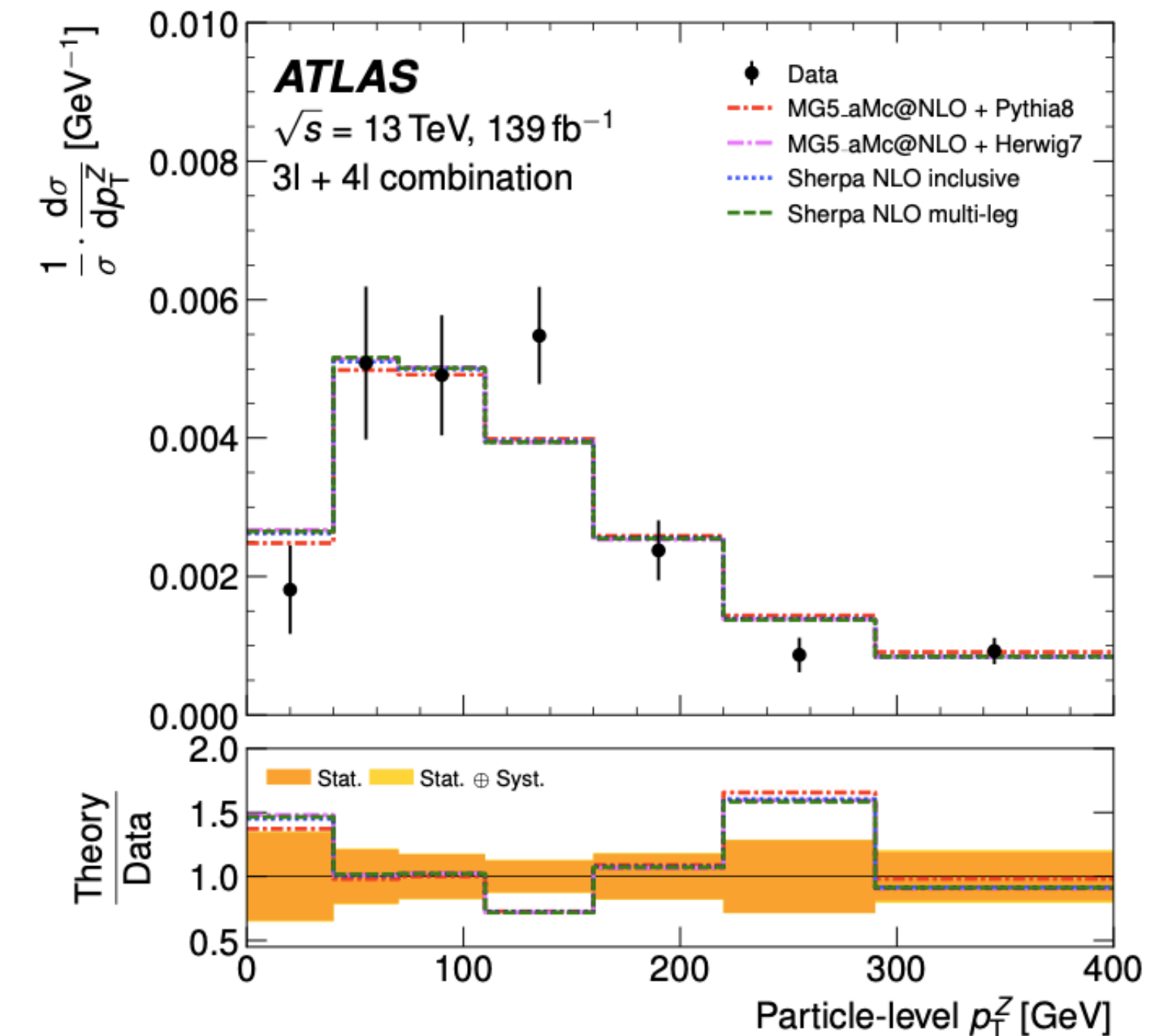


$$\sigma(t\bar{t}Z) = 0.99 \pm 0.05(\text{stat}) \pm 0.08(\text{syst}) \text{ pb}$$

with full Run-2 data (139 fb⁻¹)



Differential cross-section measurements



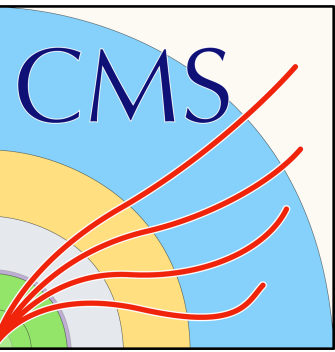
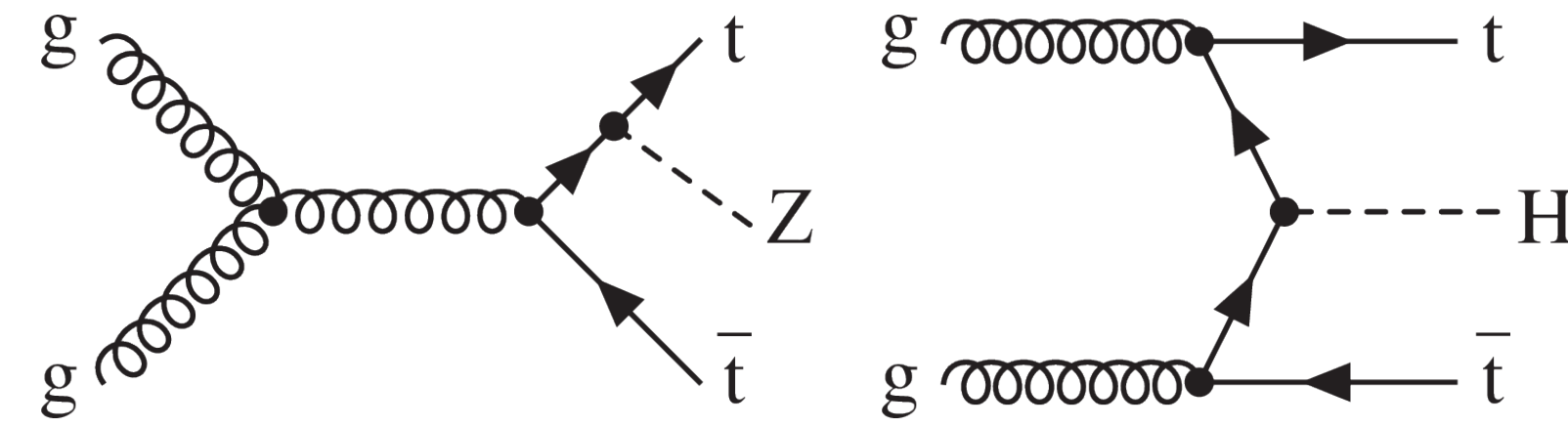
$t\bar{t}Z$ measurements

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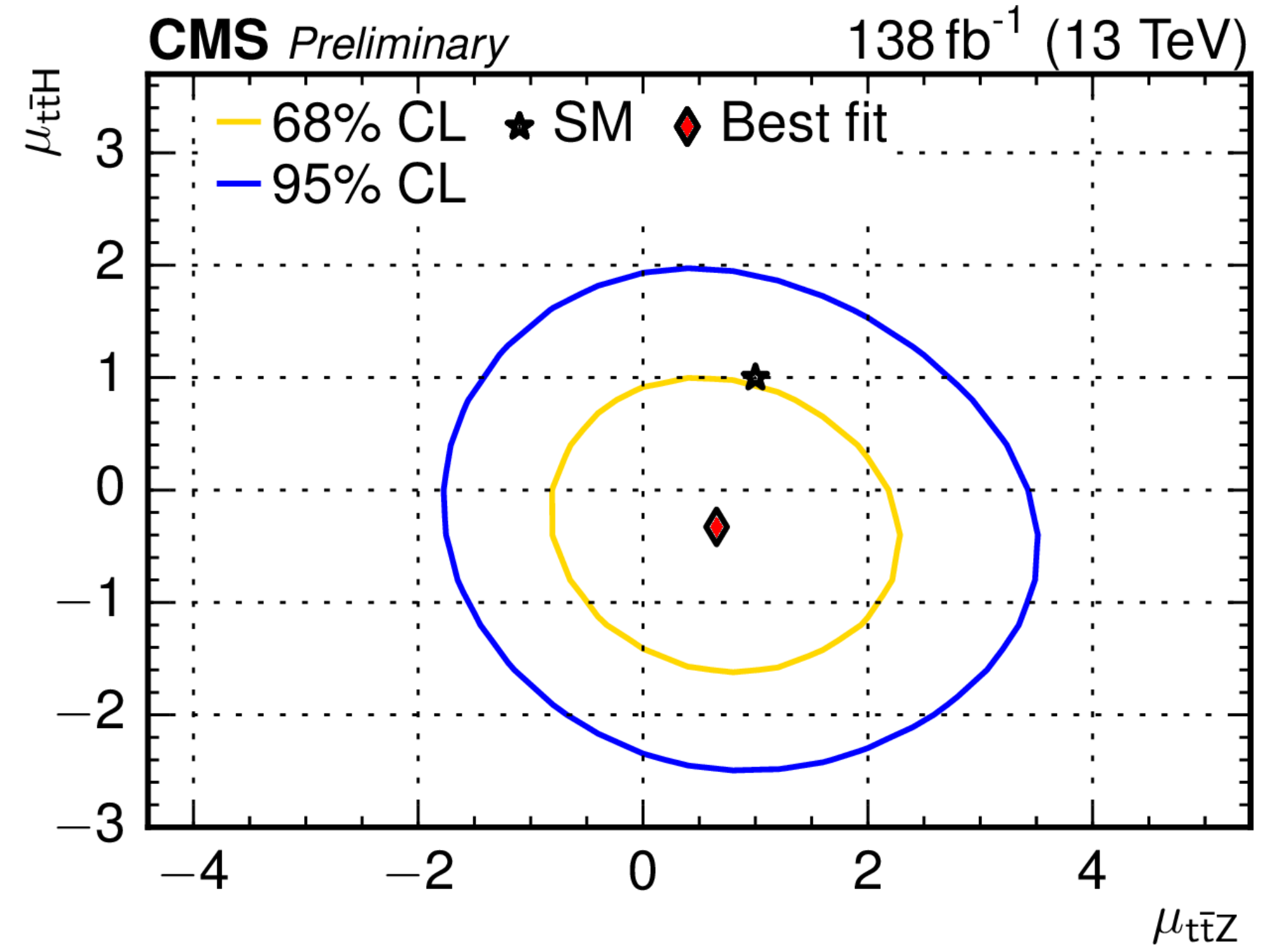
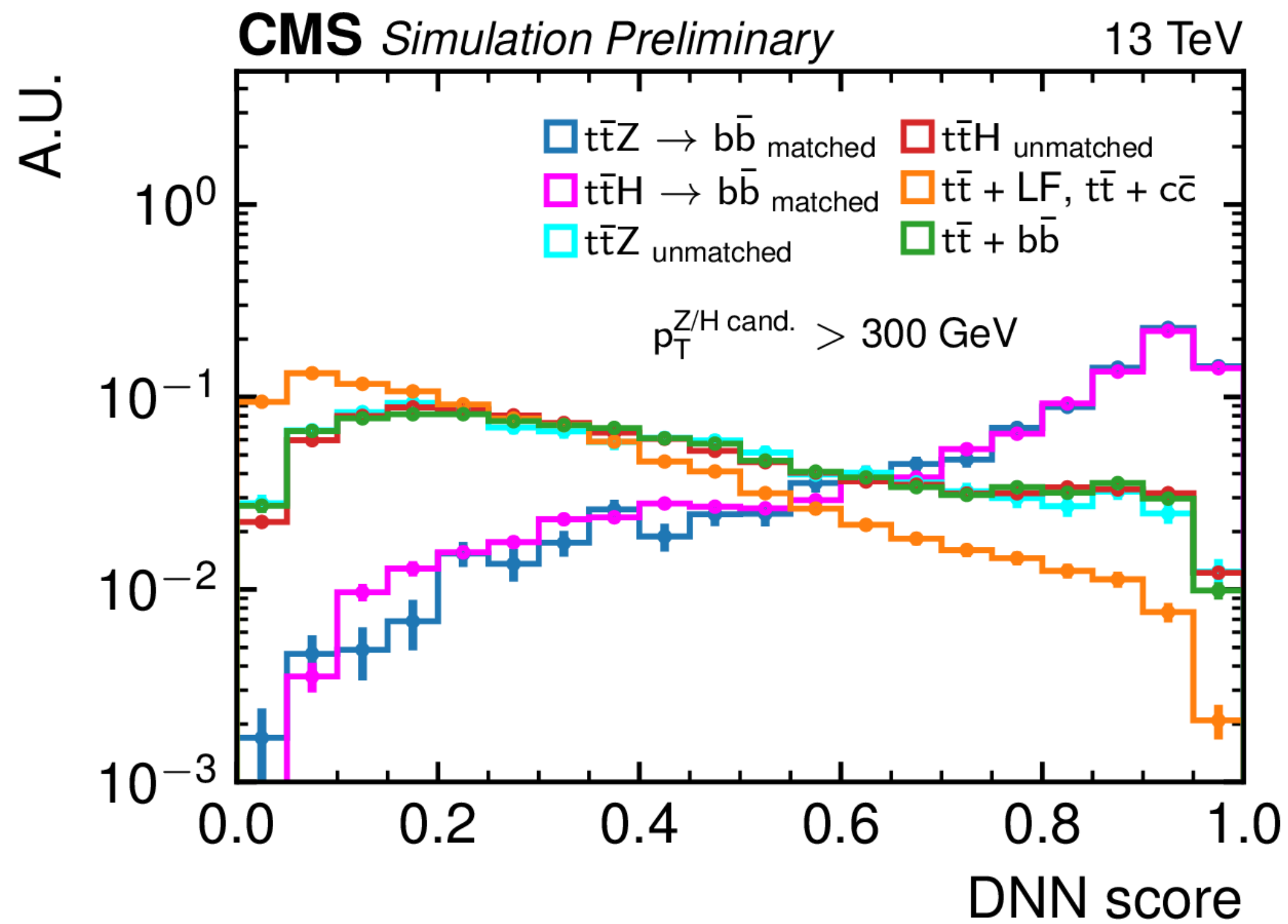
CMS-PAS-TOP-21-003

Boosted Z/H

- Search for new physics using $t\bar{t}Z$, $t\bar{t}H$ events with boosted Z/H in EFT
- High sensitivity to BSM at large p_T Z/H
- Using events with exactly 1 lepton and $Z/H \rightarrow b\bar{b}$
- Using deep NN to discriminate signal from backgrounds
- Measure signal strength of $t\bar{t}Z$ and $t\bar{t}H$
- Leading uncertainties: b-tag efficiency, $t\bar{t} + b\bar{b}$ cross section and $t\bar{t} + c\bar{c}$ cross section.



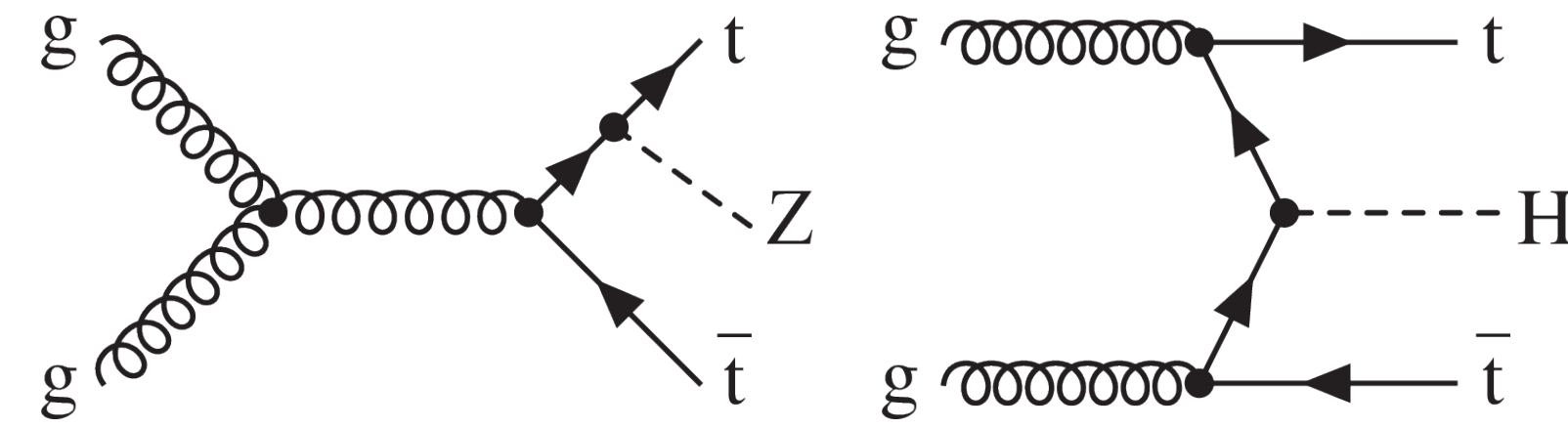
Signal strength



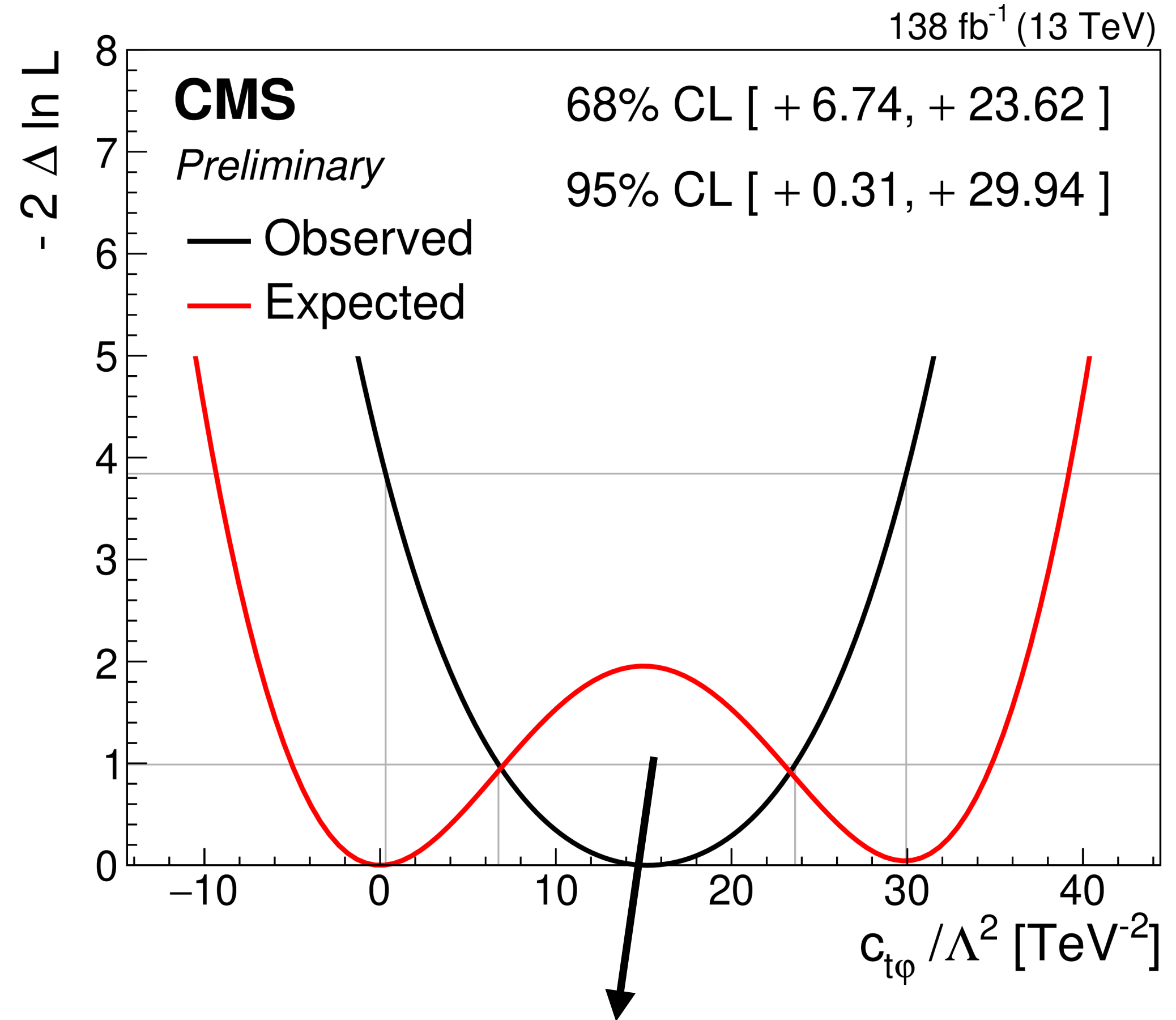
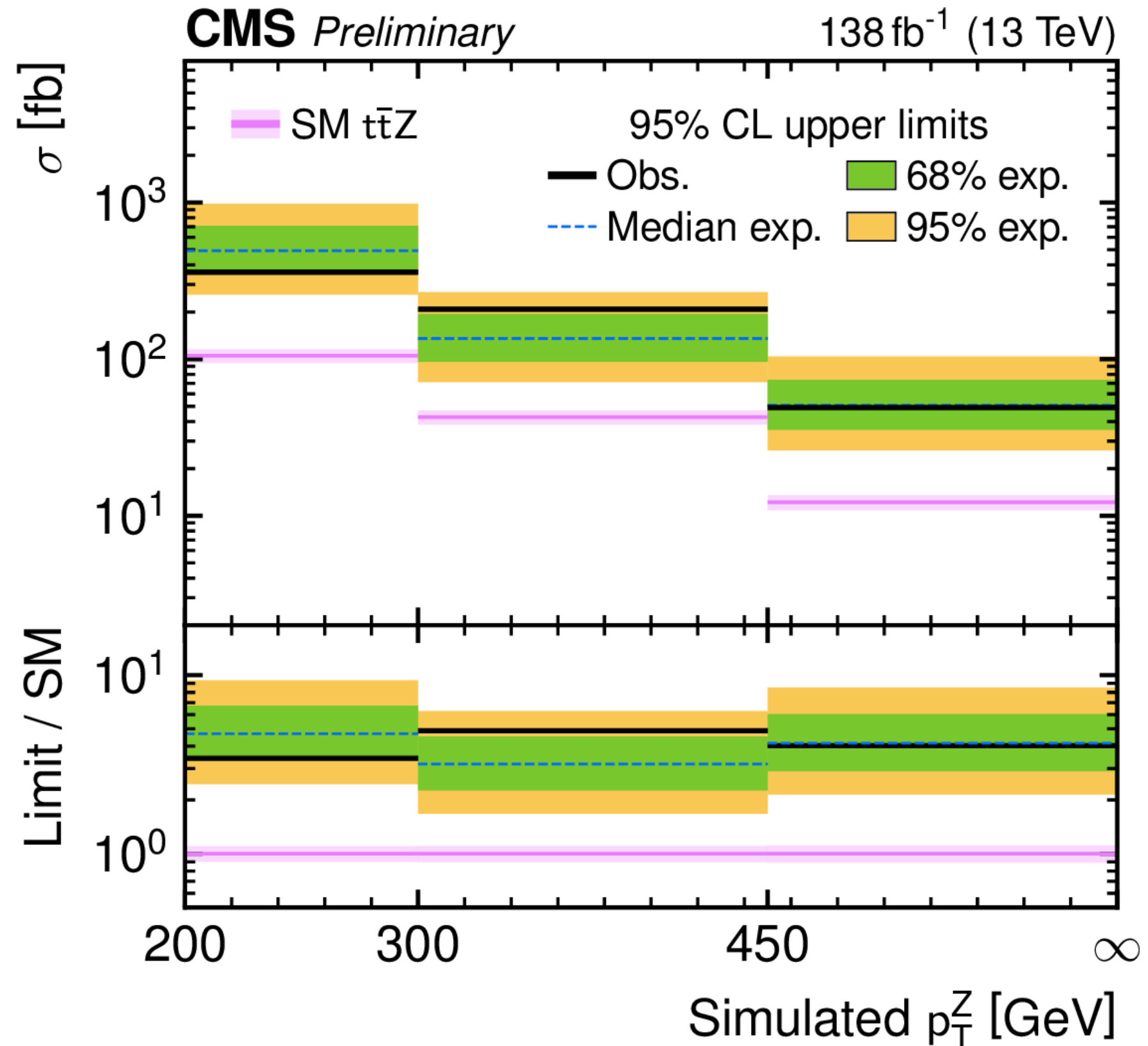
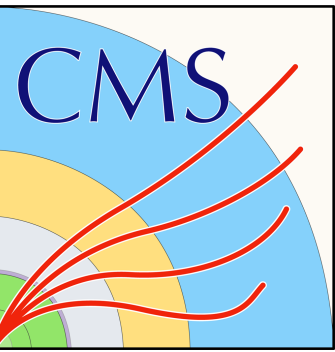
$t\bar{t}Z$ measurements

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CMS-PAS-TOP-21-003



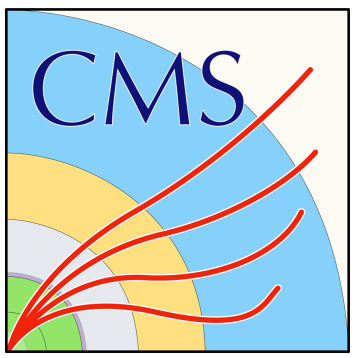
- Set 95% CL upper limit on the differential cross-sections of $t\bar{t}Z$ and $t\bar{t}H$ as function of p_T of the boson
- Present results on 8 EFT Wilson coefficients
- 7 Wilson coefficients well agree with SM



Yield of $t\bar{t}H$ smaller than SM

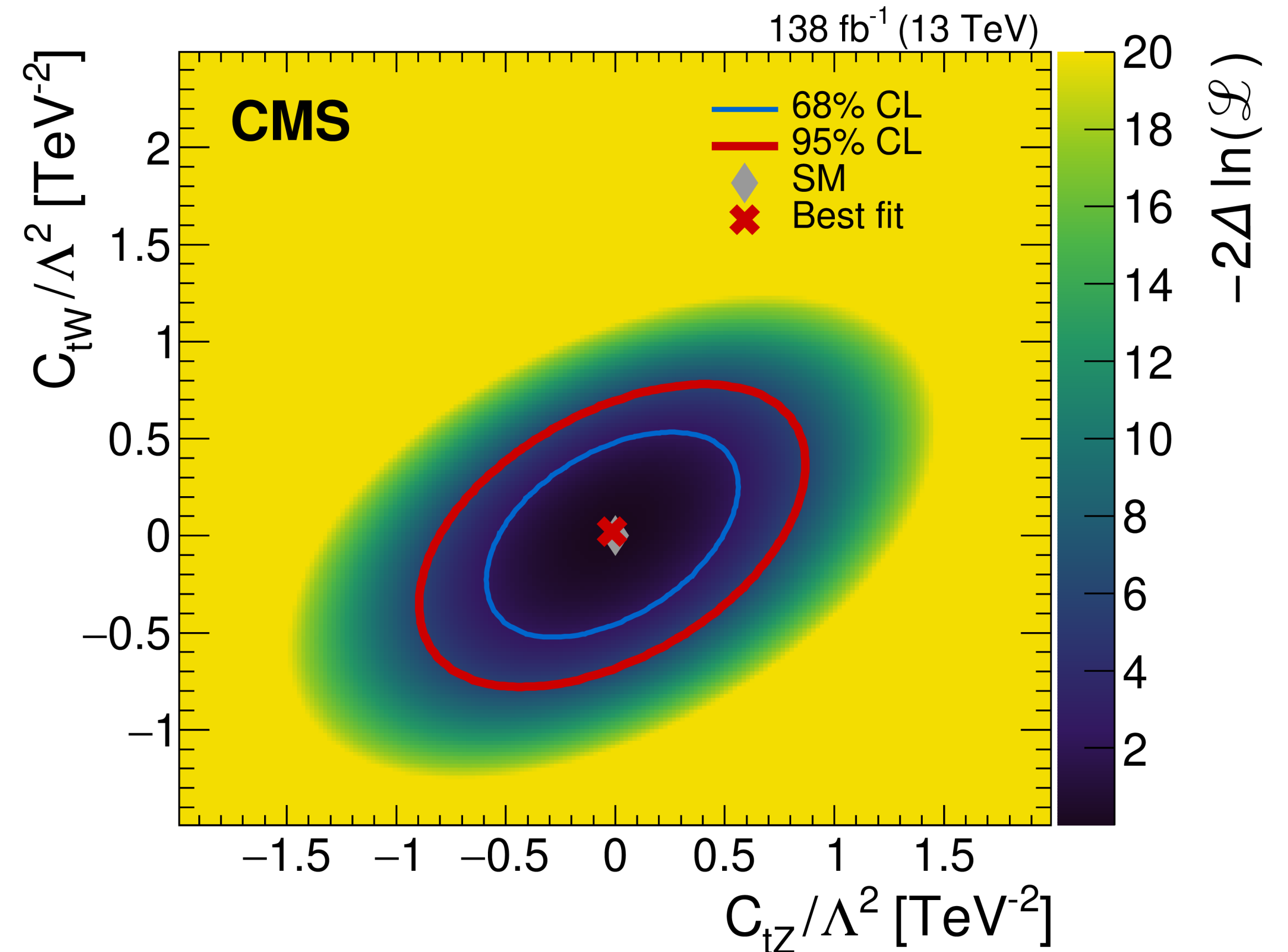
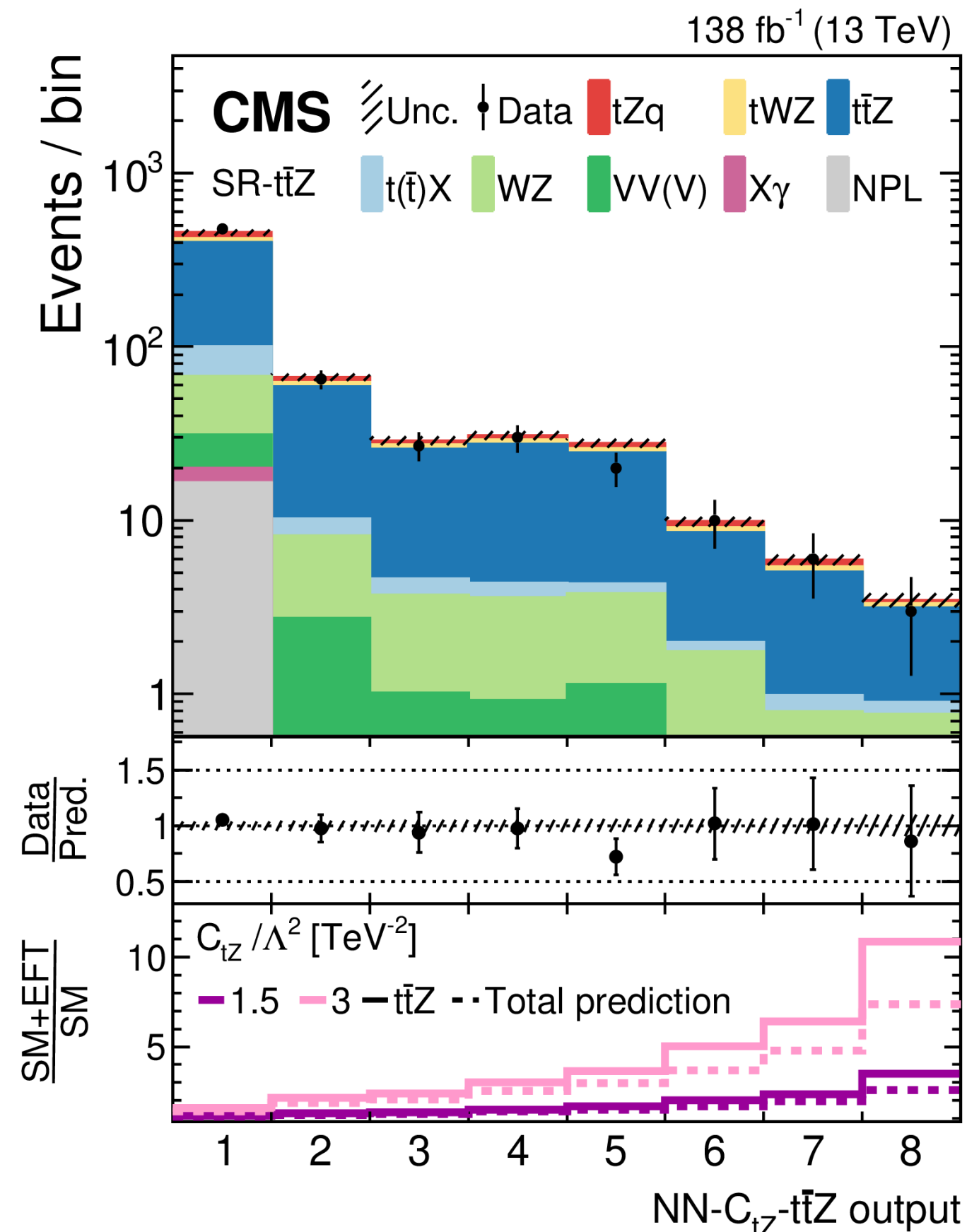
$t\bar{t}Z$ measurements EFT interpretation

JHEP 12 (2021) 083



NEW

- Measured in combination with tZq
- Using events with 3 or 4 leptons, exactly one Z candidate, ≥ 2 jets with ≥ 1 b jet
- Use MVA to classified events ($t\bar{t}Z$, tZq and others) and NNs target EFT effects
- 5 dimension-six operators are studied
- The results are consistent with SM



$t\bar{t}\gamma$ measurements

Inclusive cross-section in fiducial phase-spaces

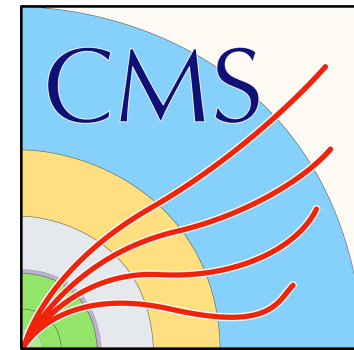
- Full Run-II data (138 fb⁻¹)

- [JHEP 12 \(2021\) 180](#)

- Single lepton, ≥ 1 b jet

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

- $\sigma_{SM}(t\bar{t}\gamma) = 773 \pm 135$ fb



- [CMS-TOP-21-004](#)

- Opposite-sign dilepton, ≥ 1 b jet

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

- $\sigma_{SM}(t\bar{t}\gamma) = 153 \pm 27$ fb



- Full Run-II data (139 fb⁻¹)

- [JHEP 09 \(2020\) 049](#)

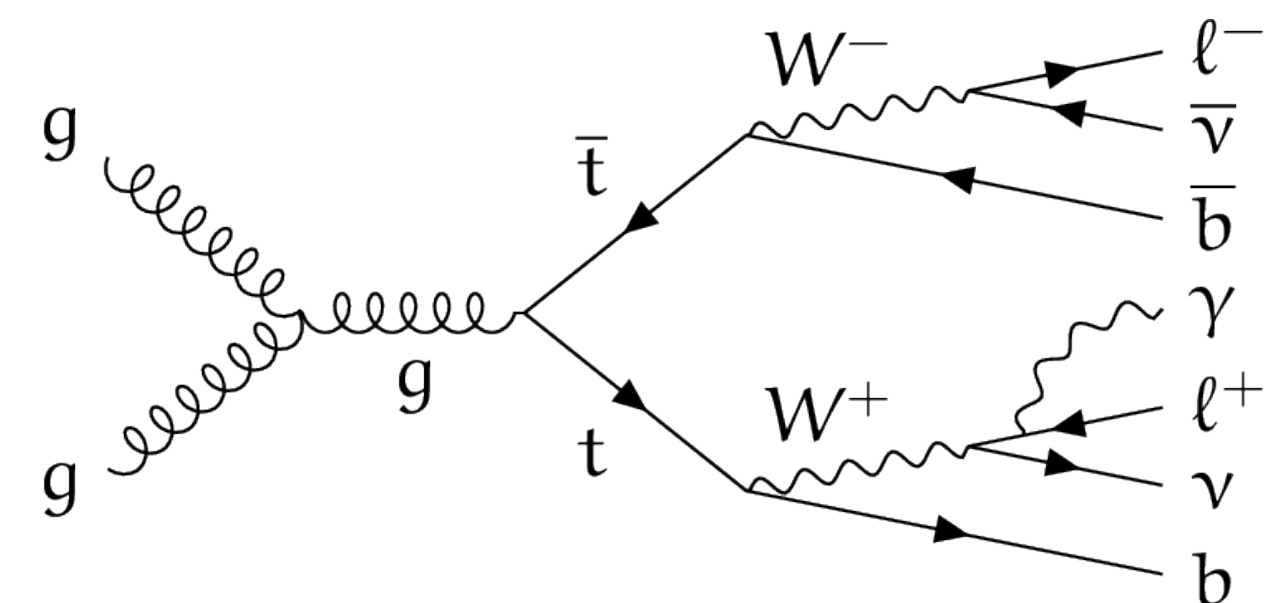
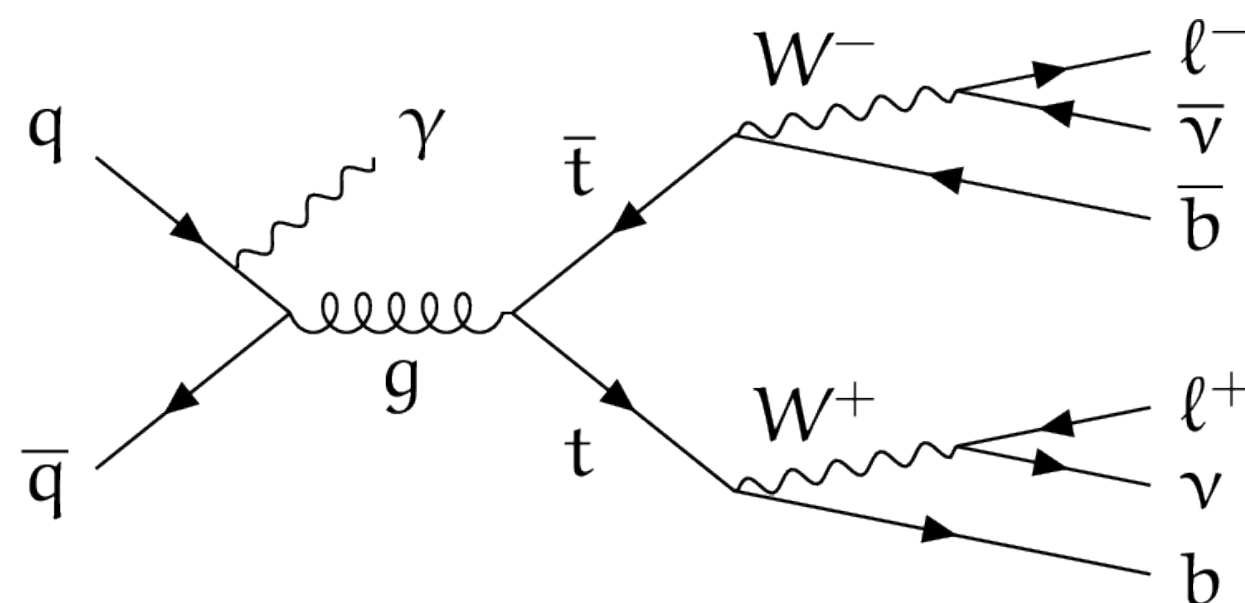
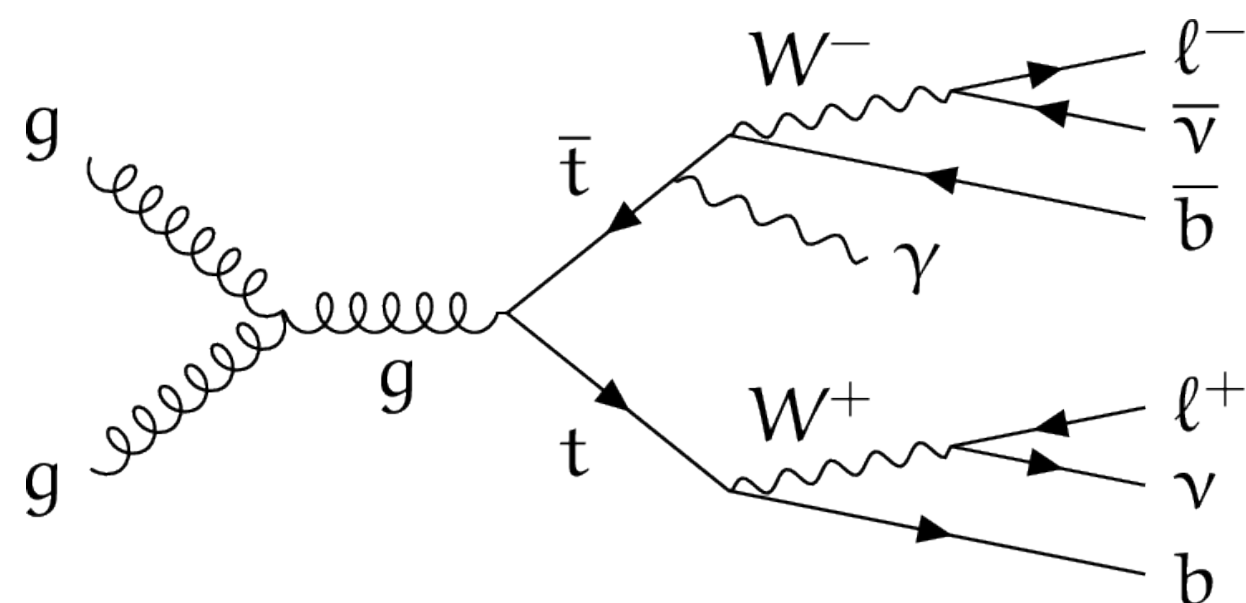
- Combination: $t\bar{t}\gamma + tW\gamma$

- $e^\pm\mu^\mp$, ≥ 2 jets with ≥ 1 b jet

- $\sigma(t\bar{t}\gamma + tW\gamma) = 39.6 \pm 0.8$ (stat) $^{+2.6}_{-2.2}$ (syst) fb

- $\sigma_{SM}(t\bar{t}\gamma + tW\gamma) = 38.50^{+0.56}_{-2.18}$ (scale) $^{+1.04}_{-1.18}$ (PDF) fb

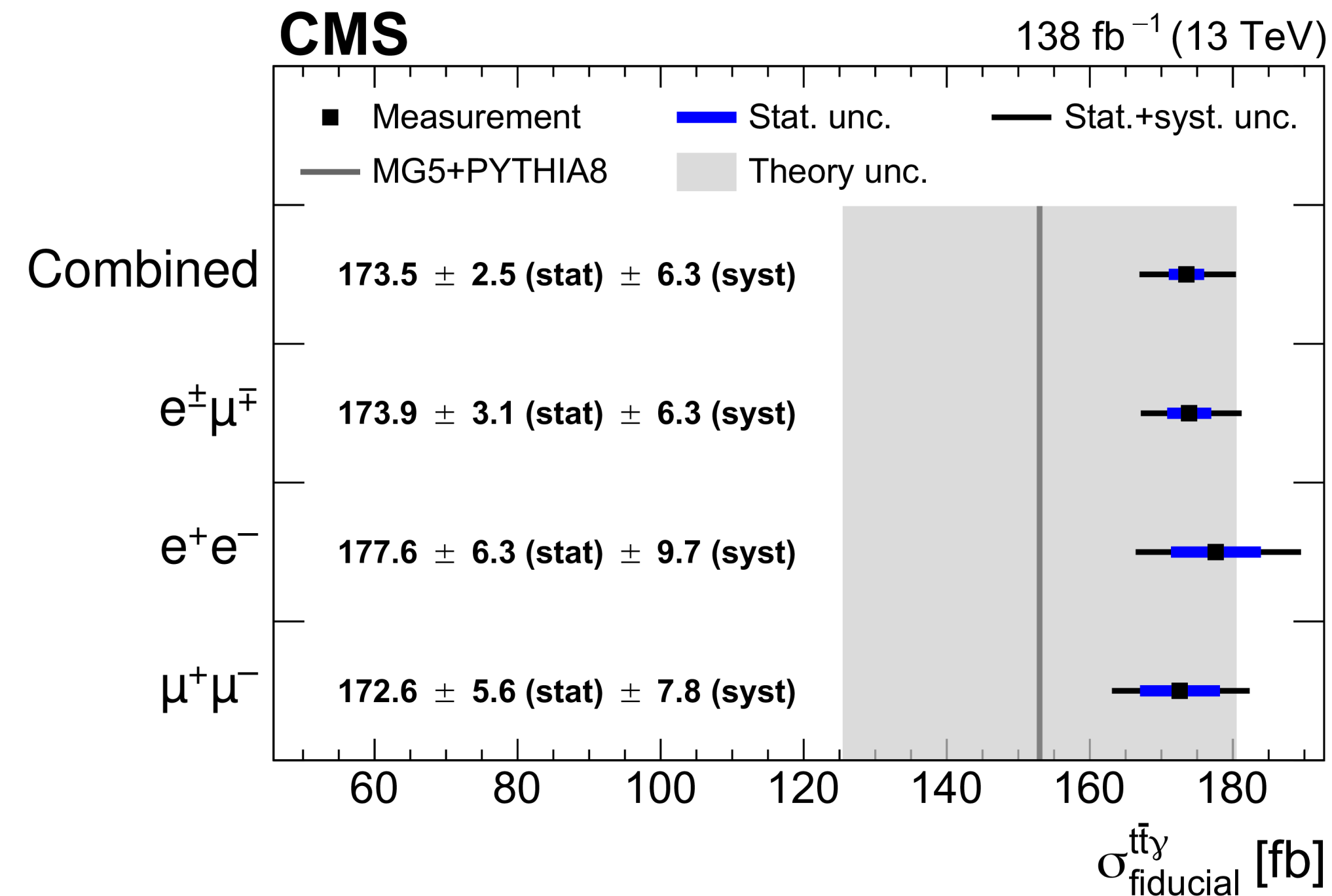
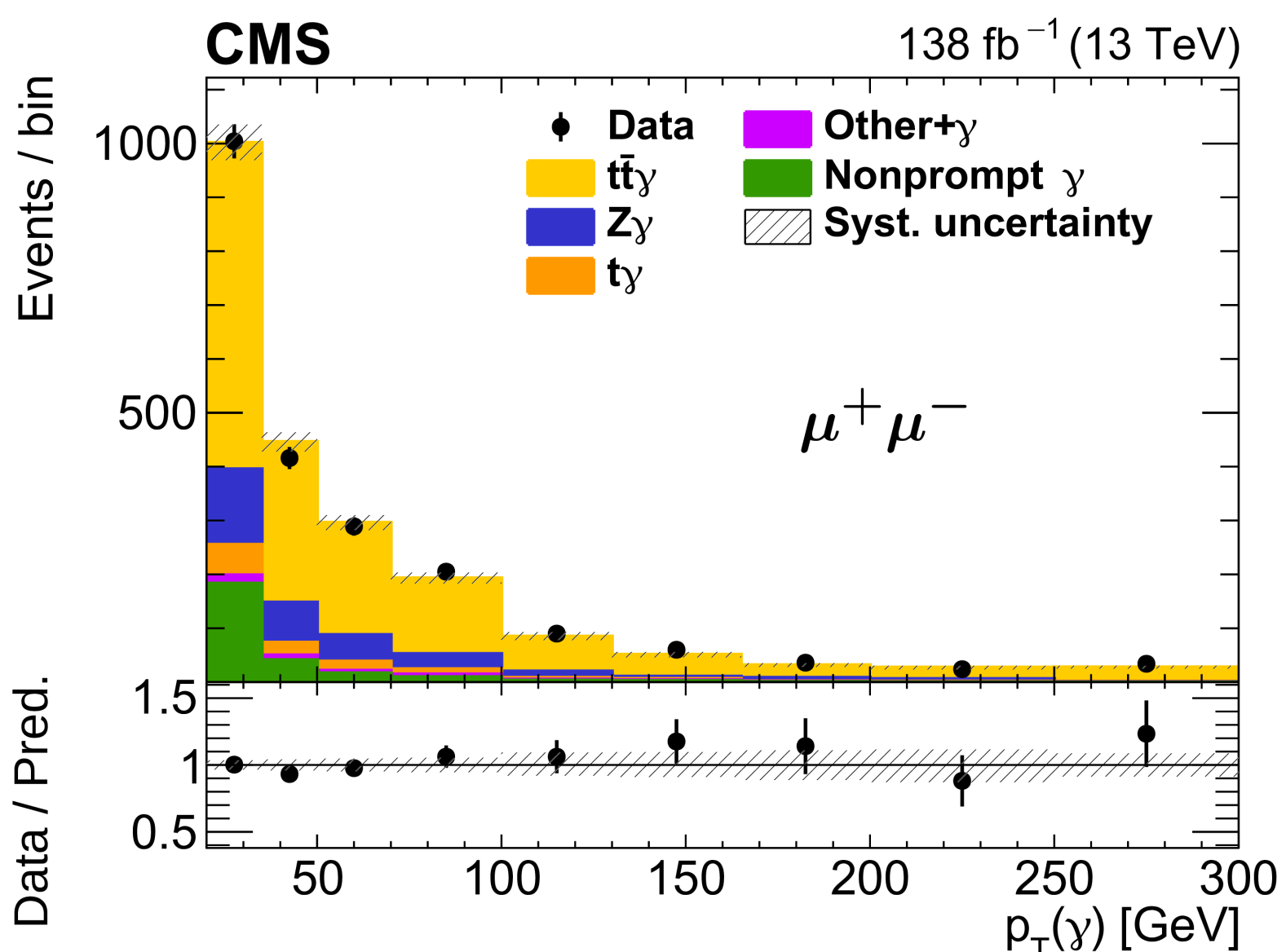
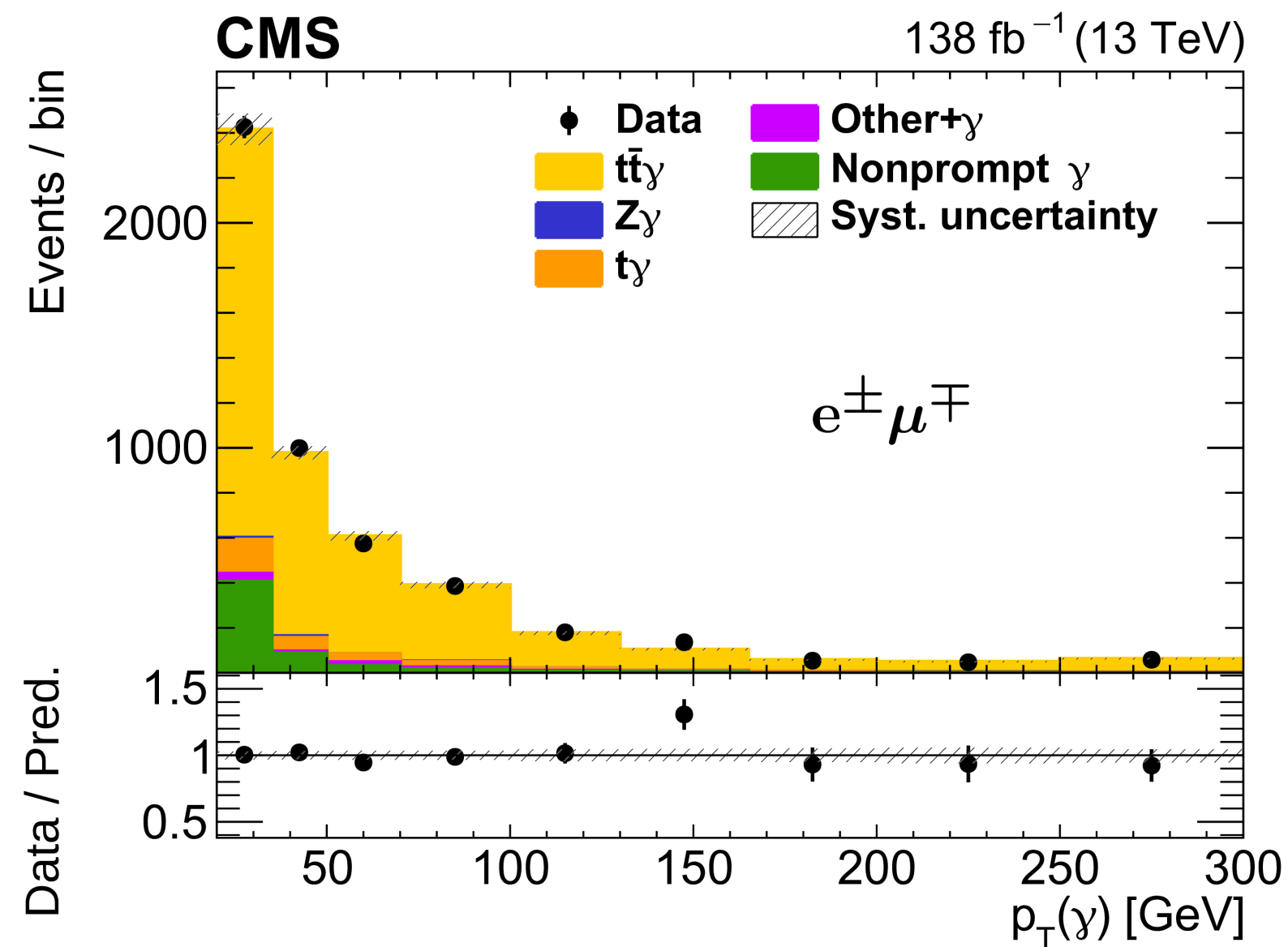
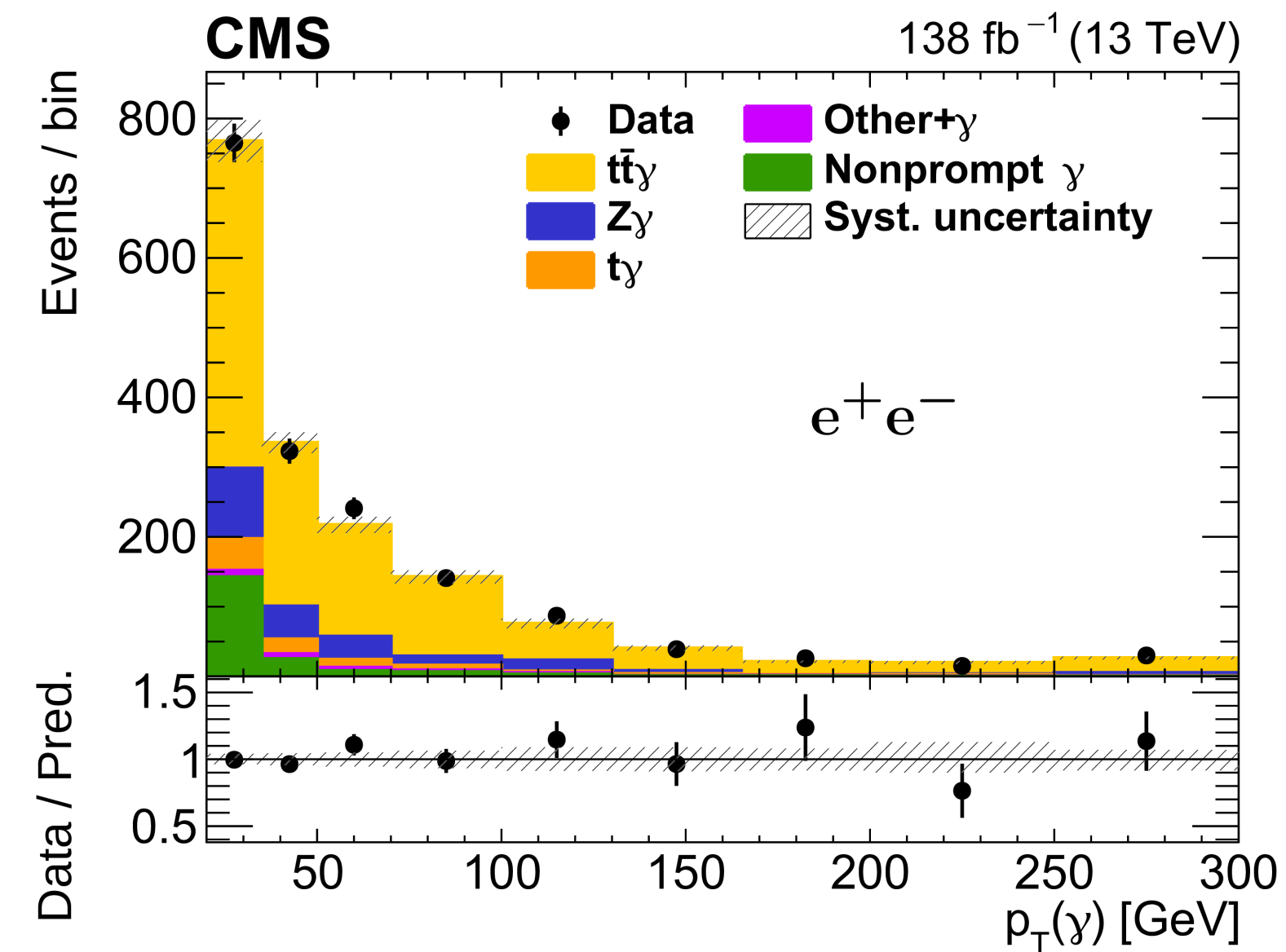
Consistent with predictions



$t\bar{t}\gamma$ measurements

Inclusive cross-section

CMS-TOP-21-004



- Leading uncertainties:
 - Integrated luminosity (1.7%)
 - Parton-shower modelling: ISR & FSR scale; value of μ_F and μ_R (1.3%)
 - Photon selection efficiency and b-tag efficiency (1.1%)

Theory

$$\sigma_{SM}(t\bar{t}\gamma) = 153 \pm 27 \text{ fb}$$

$t\bar{t}\gamma$ measurements

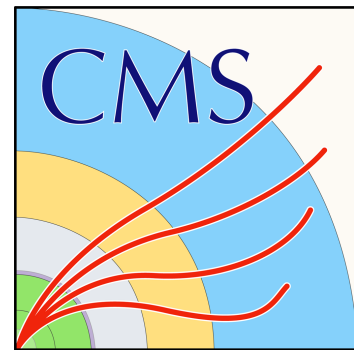
Differential cross-section

- Measured as functions of several kinematic observables of the photon, leptons, and jets
- Consistent with predictions calculated from MadGraph5 aMC@NLO



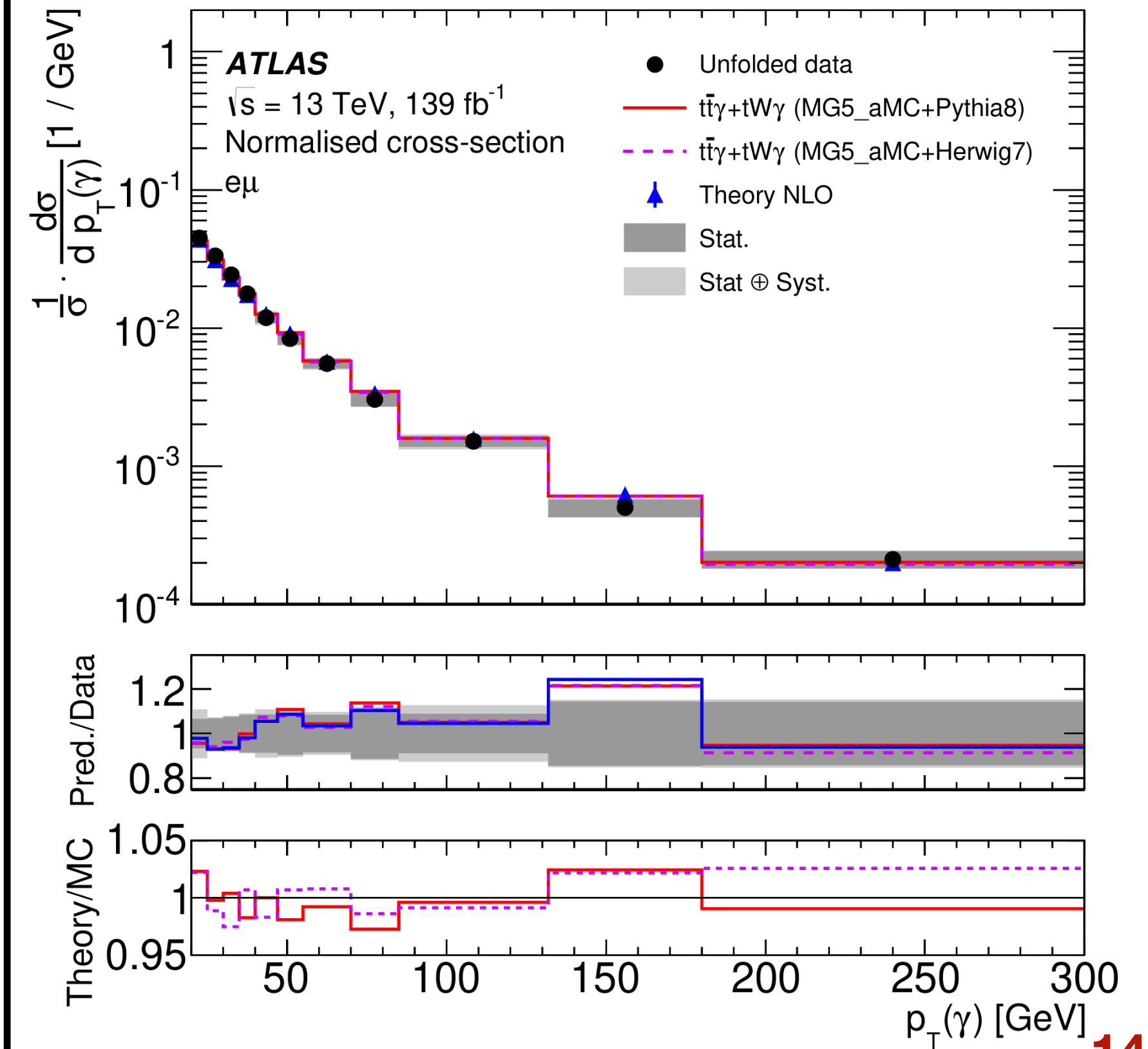
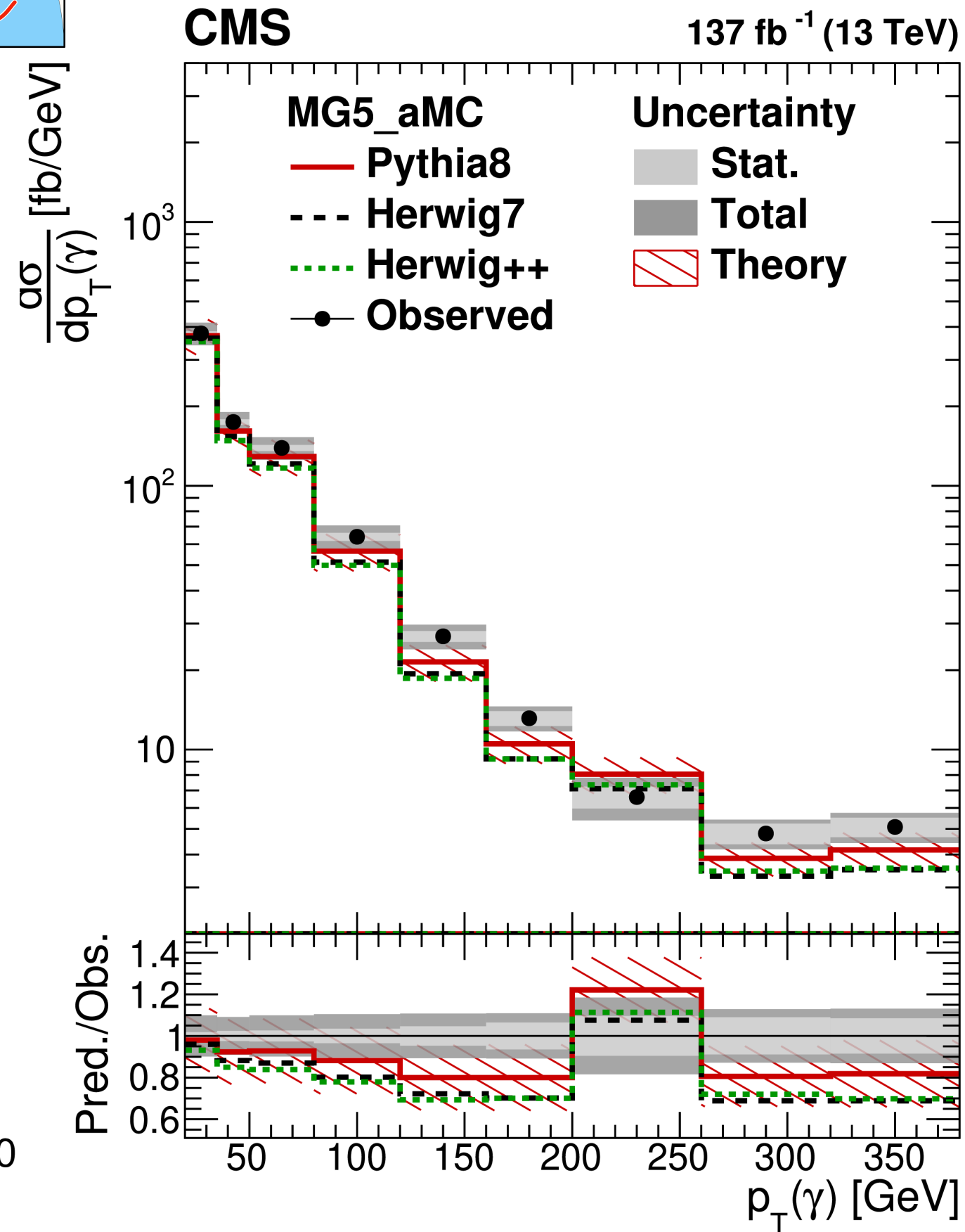
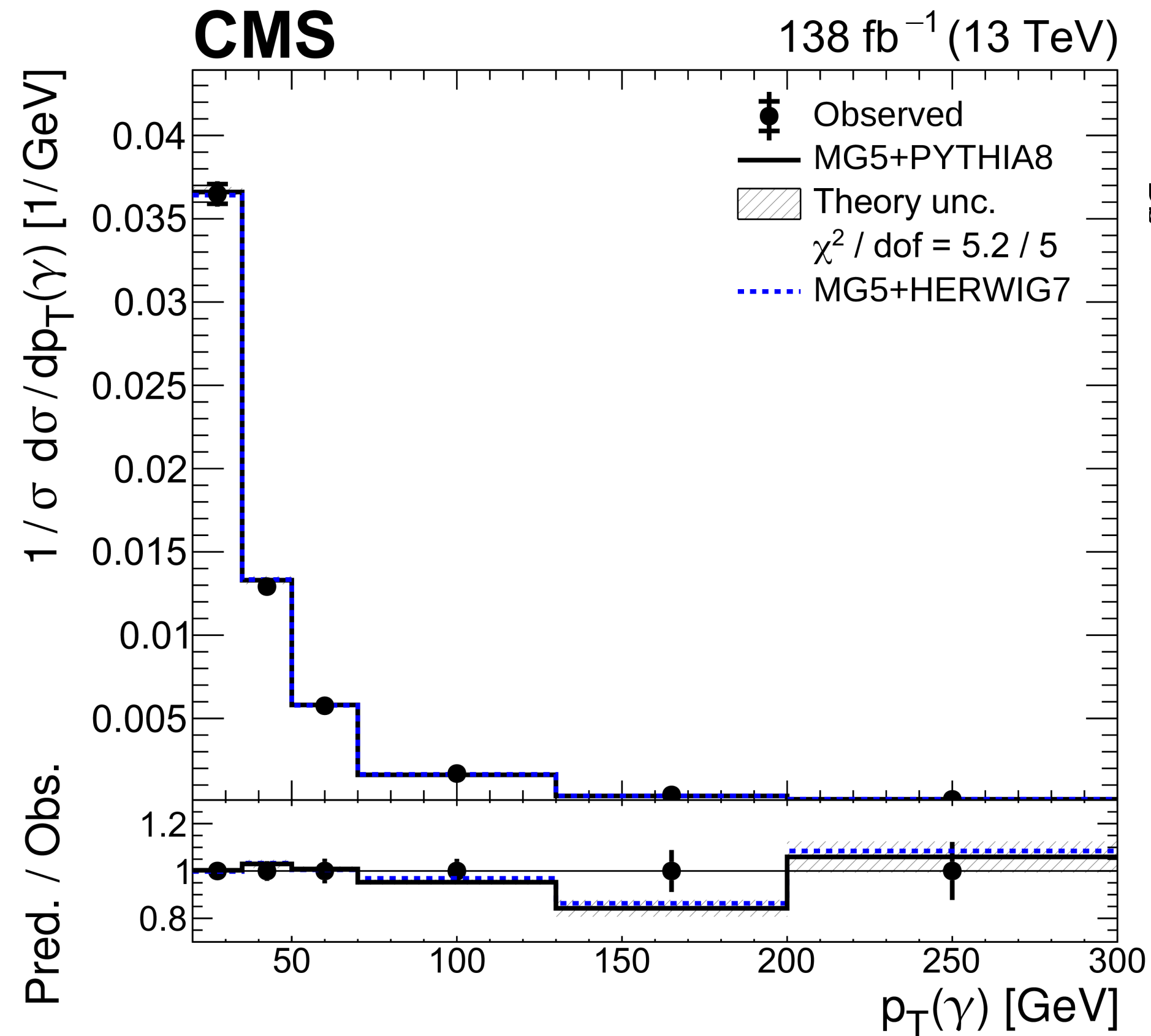
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JHEP 12 (2021) 180

JHEP 09 (2020) 049



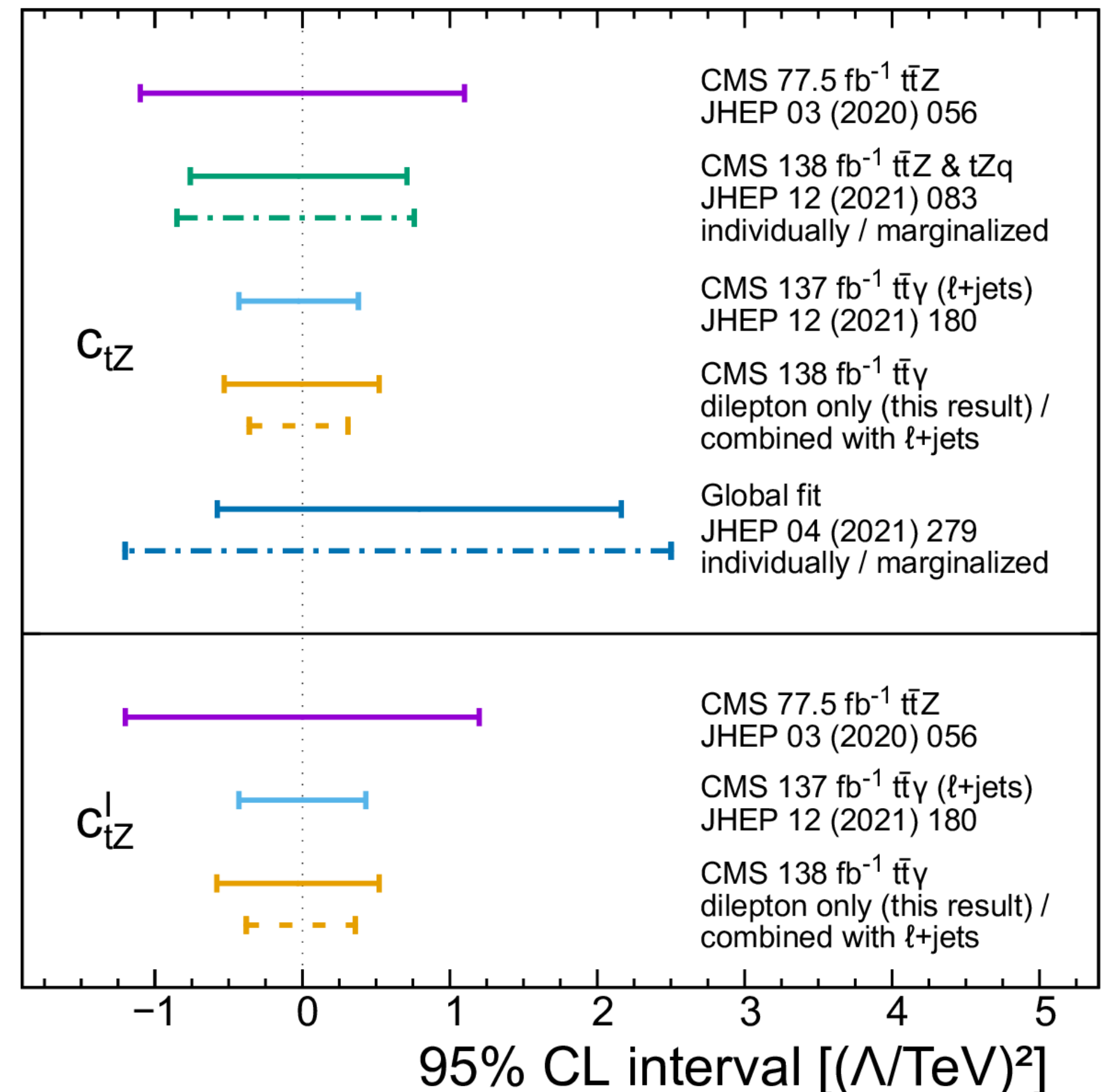
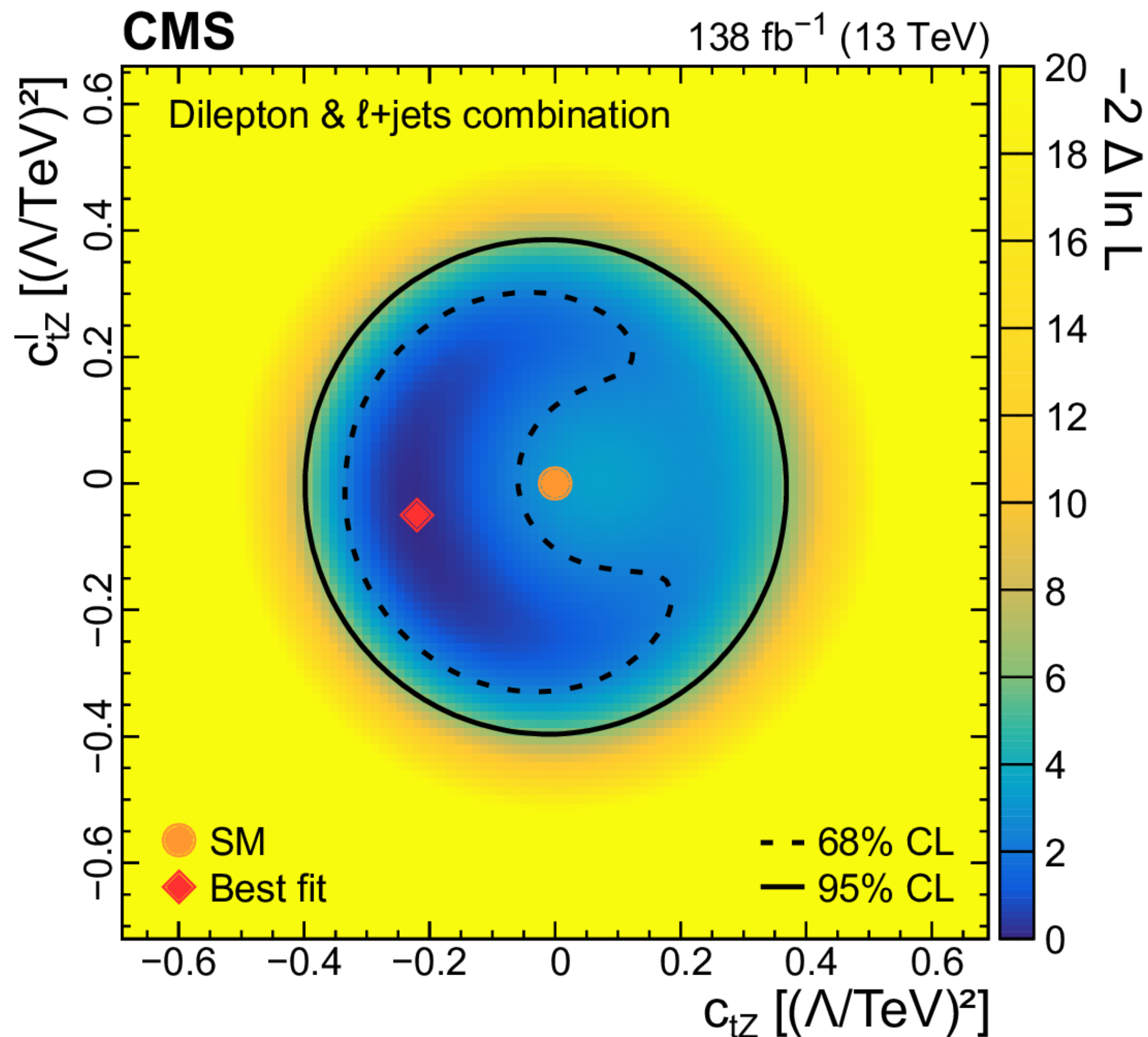
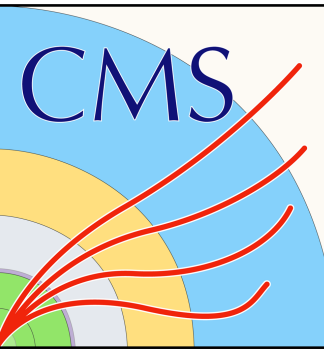
$t\bar{t}\gamma$ measurements

EFT interpretation

- Results from dilepton and dilepton+single lepton
- Limits found in c_{tZ} and c_{tZ}^I Wilson coefficients which describe the modifications of $t\bar{t}\gamma$ and $t\bar{t}Z$ interaction vertices

CMS-TOP-21-004

NEW



Summary

- Report new $t\bar{t}V$ results with full Run-2 data
- Probing rare SM processes, as well as their differential cross section
- New $t\bar{t}W$ inclusive cross section measurements from CMS using dilepton and three-lepton channels
- First study of $t\bar{t}Z$ and $t\bar{t}H$ using boosted Z and H bosons
- EFT interpretation using $t\bar{t}Z/\gamma$ events
- The results are in agreement with SM within 2σ
- New results are coming with LHC Run-3 data

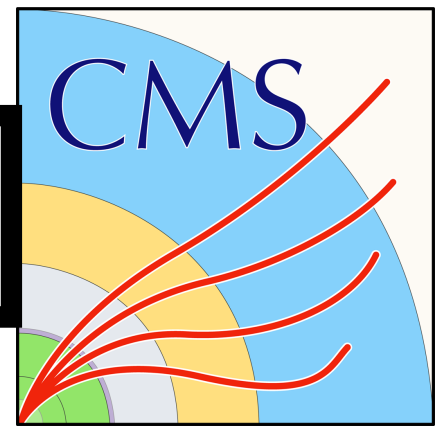
Thank you

Backup

$t\bar{t}W$ measurement from CMS

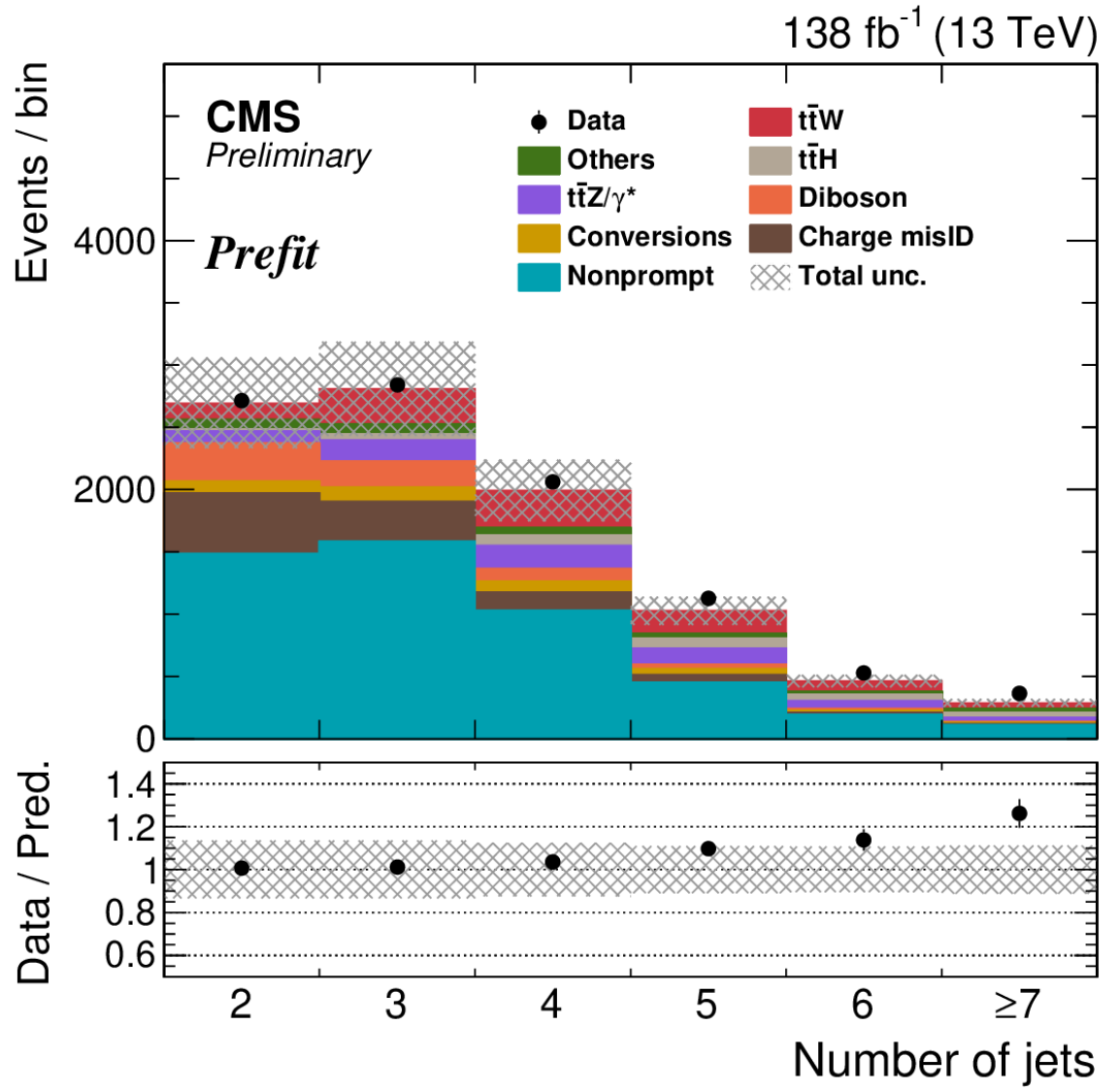
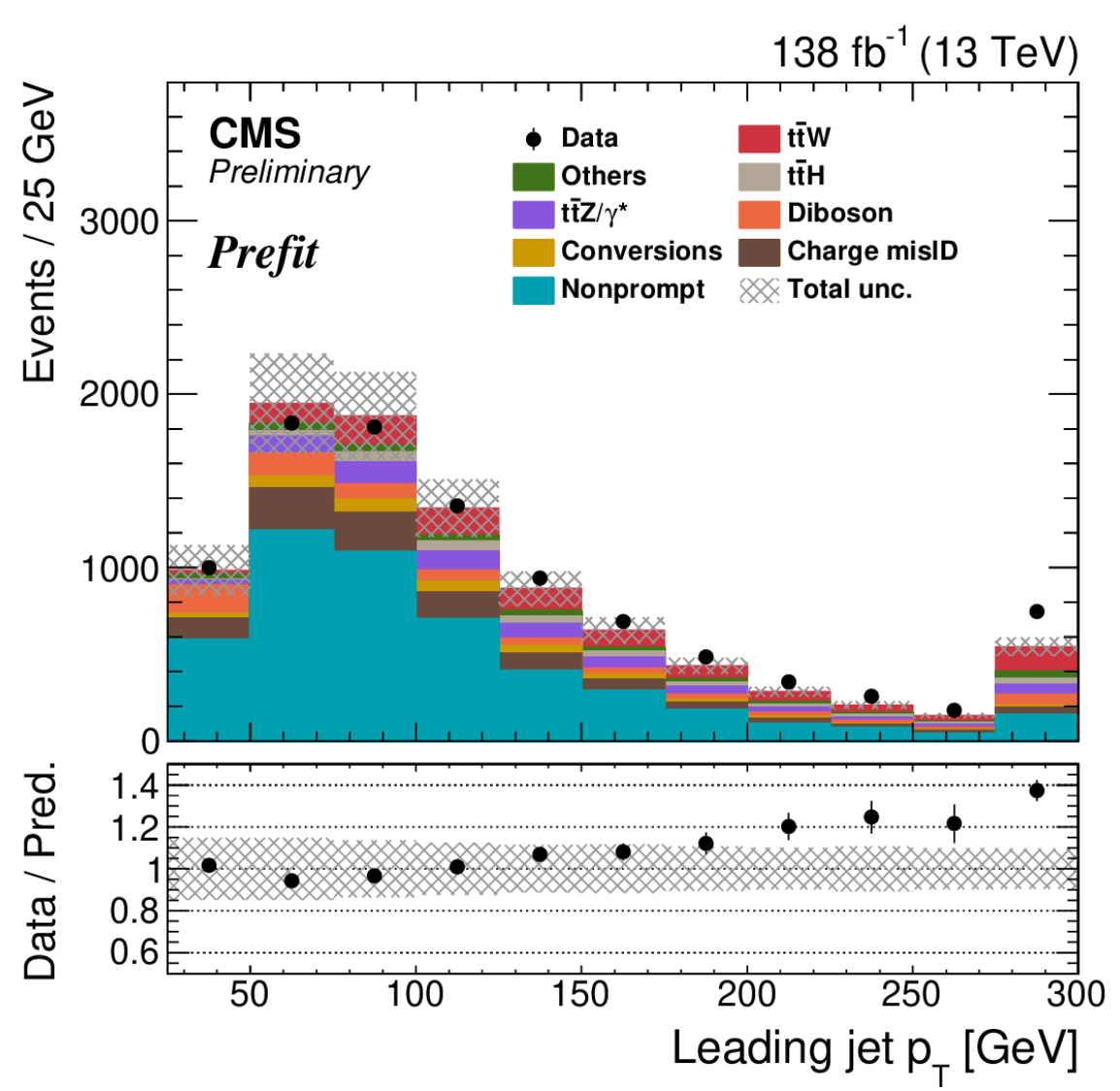
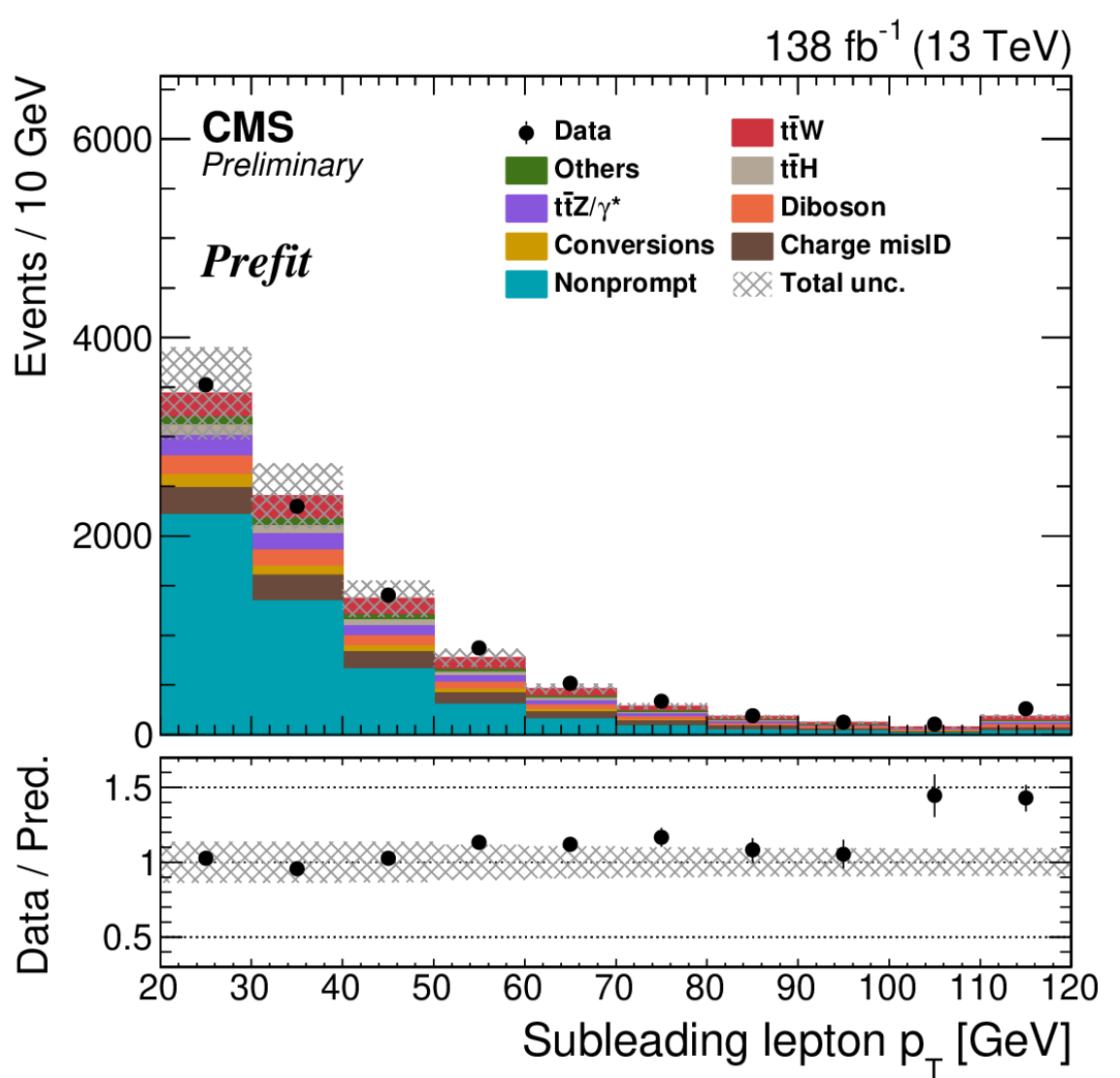
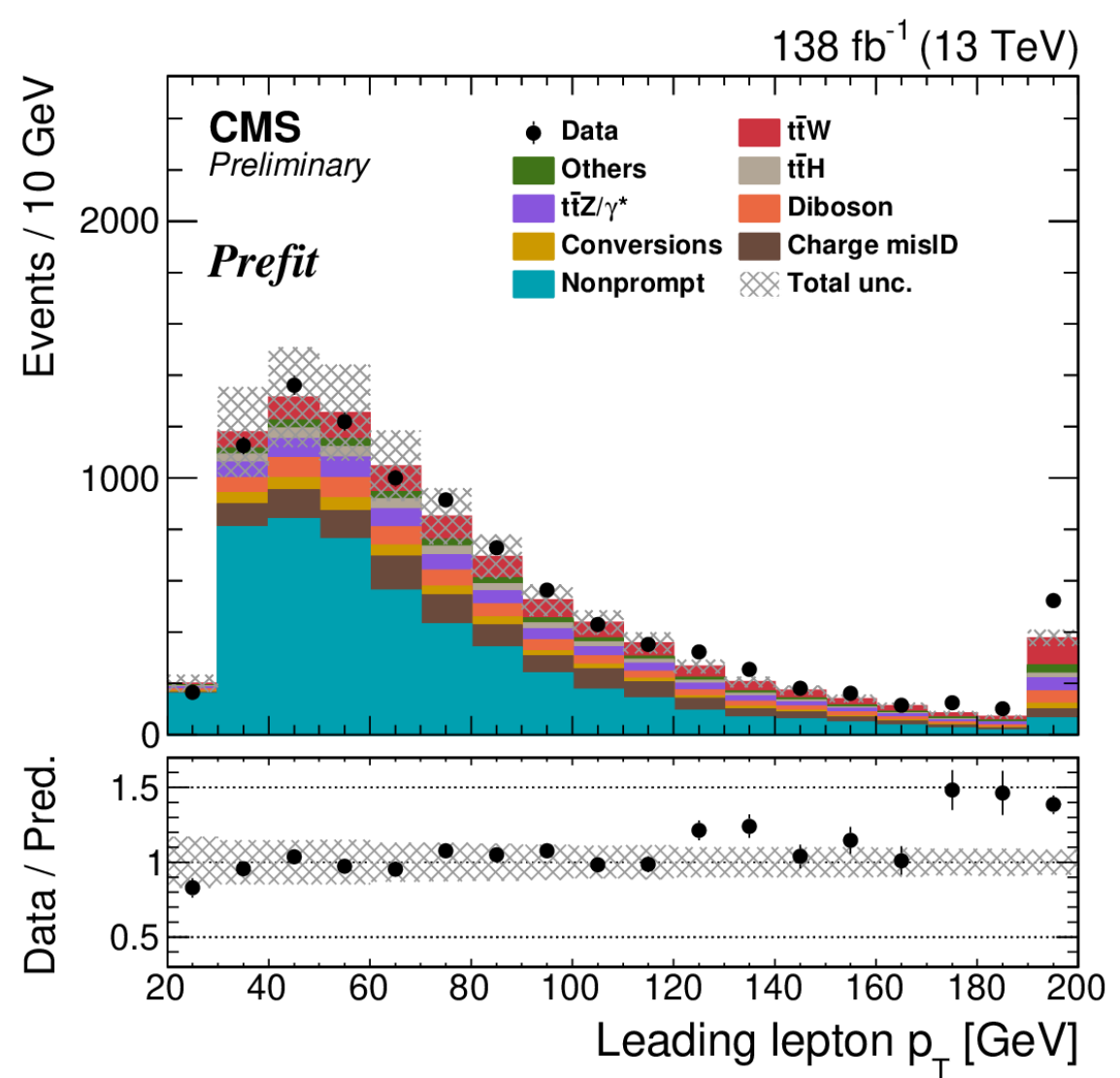
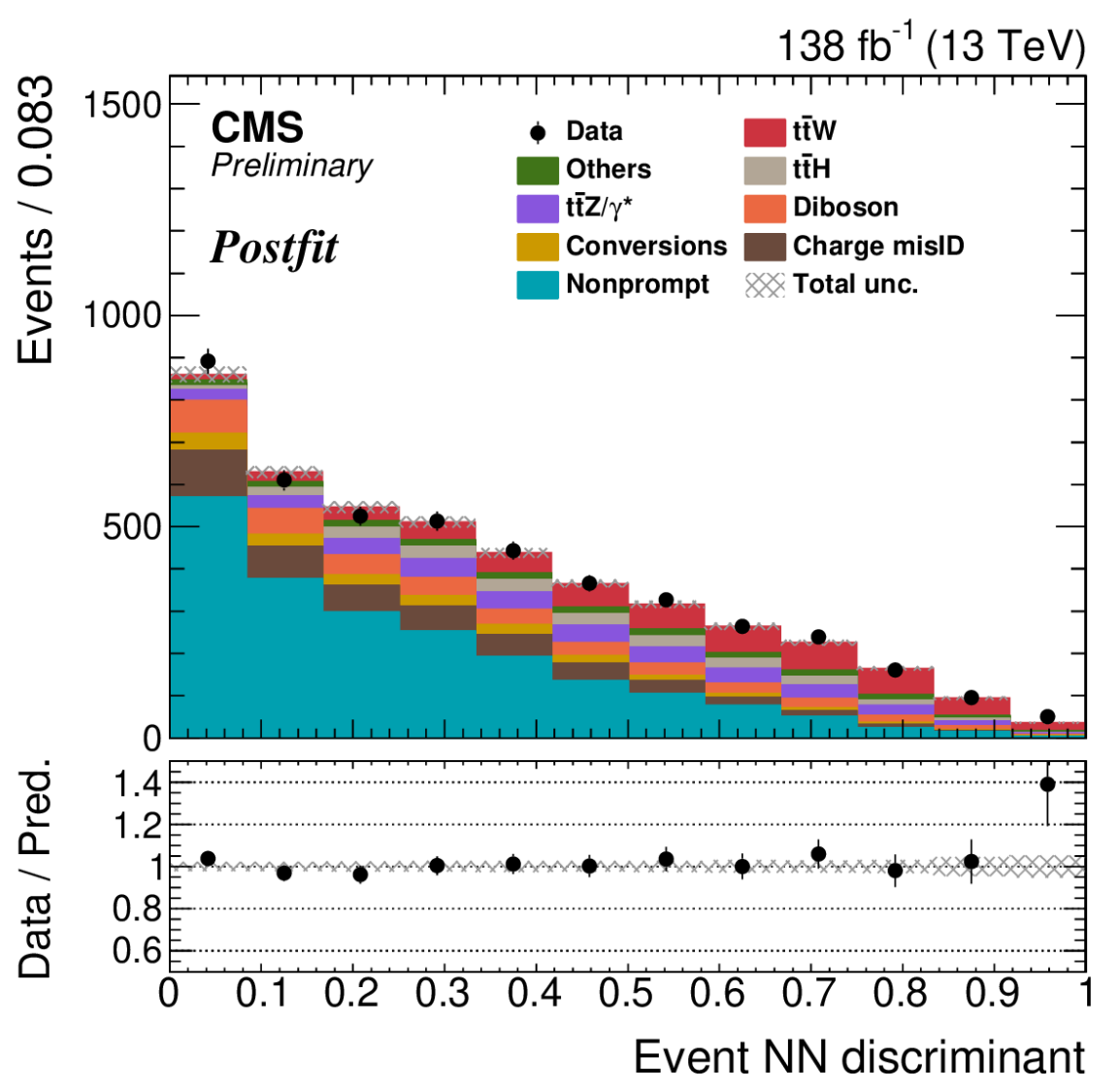
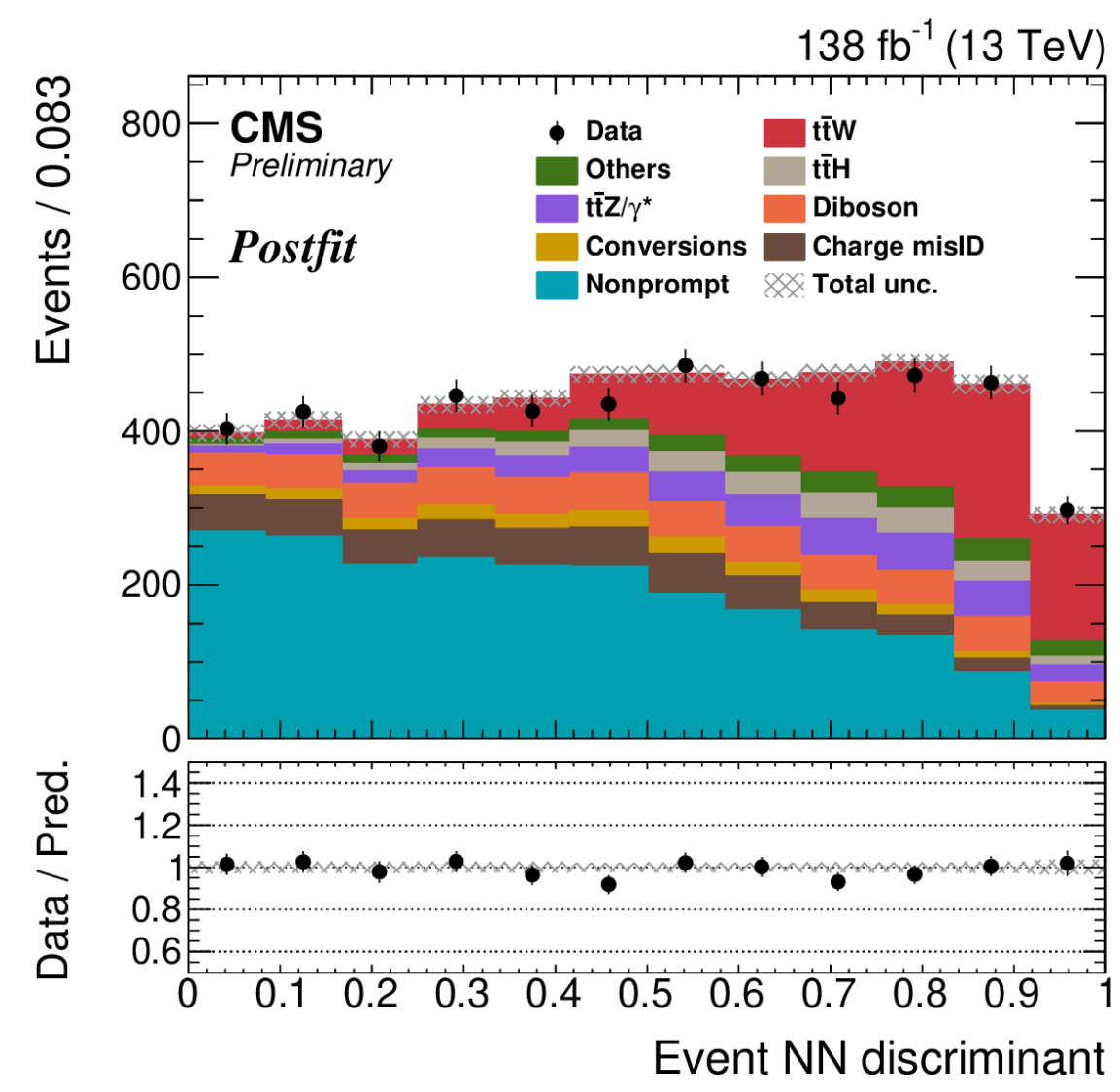
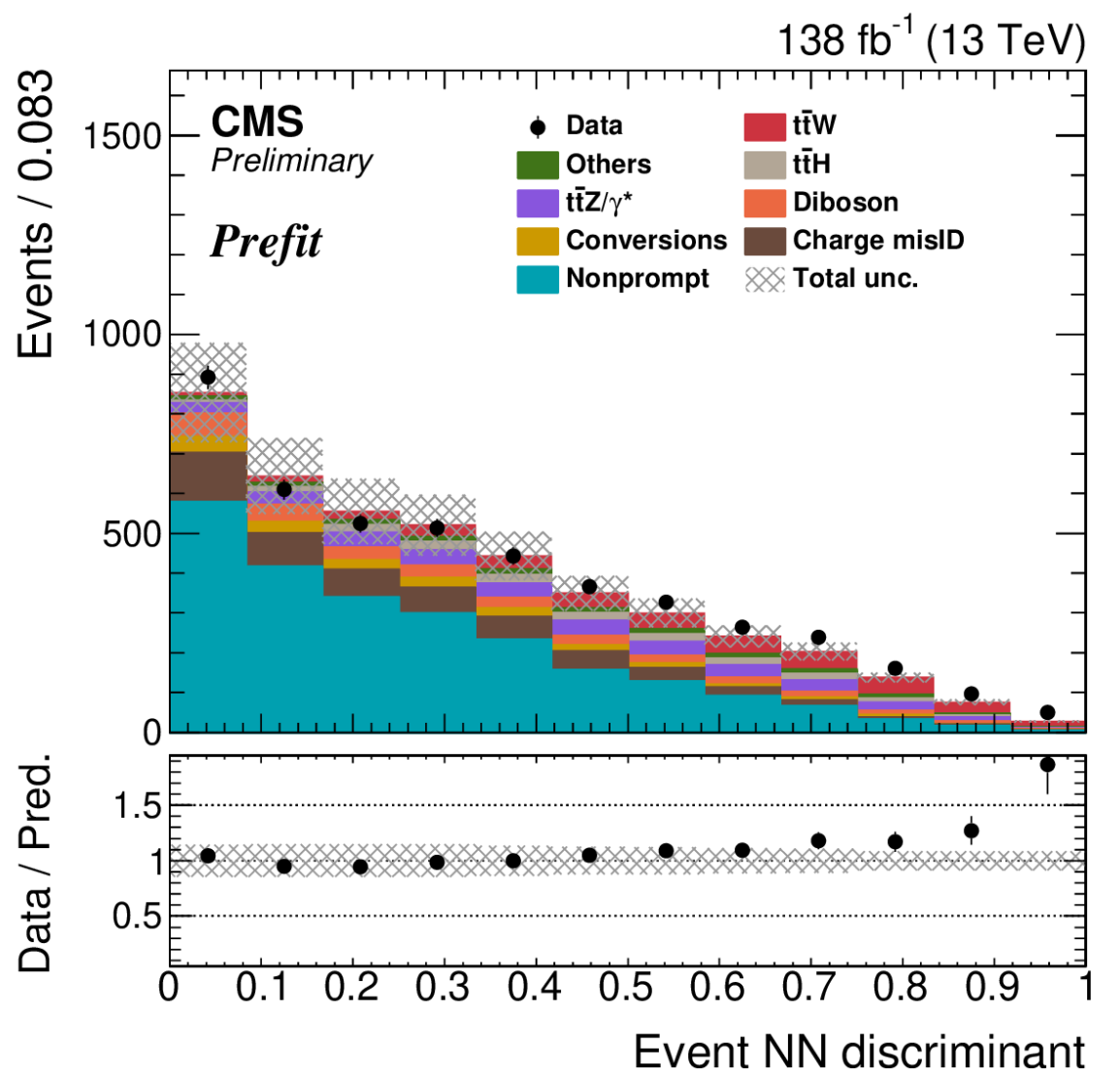
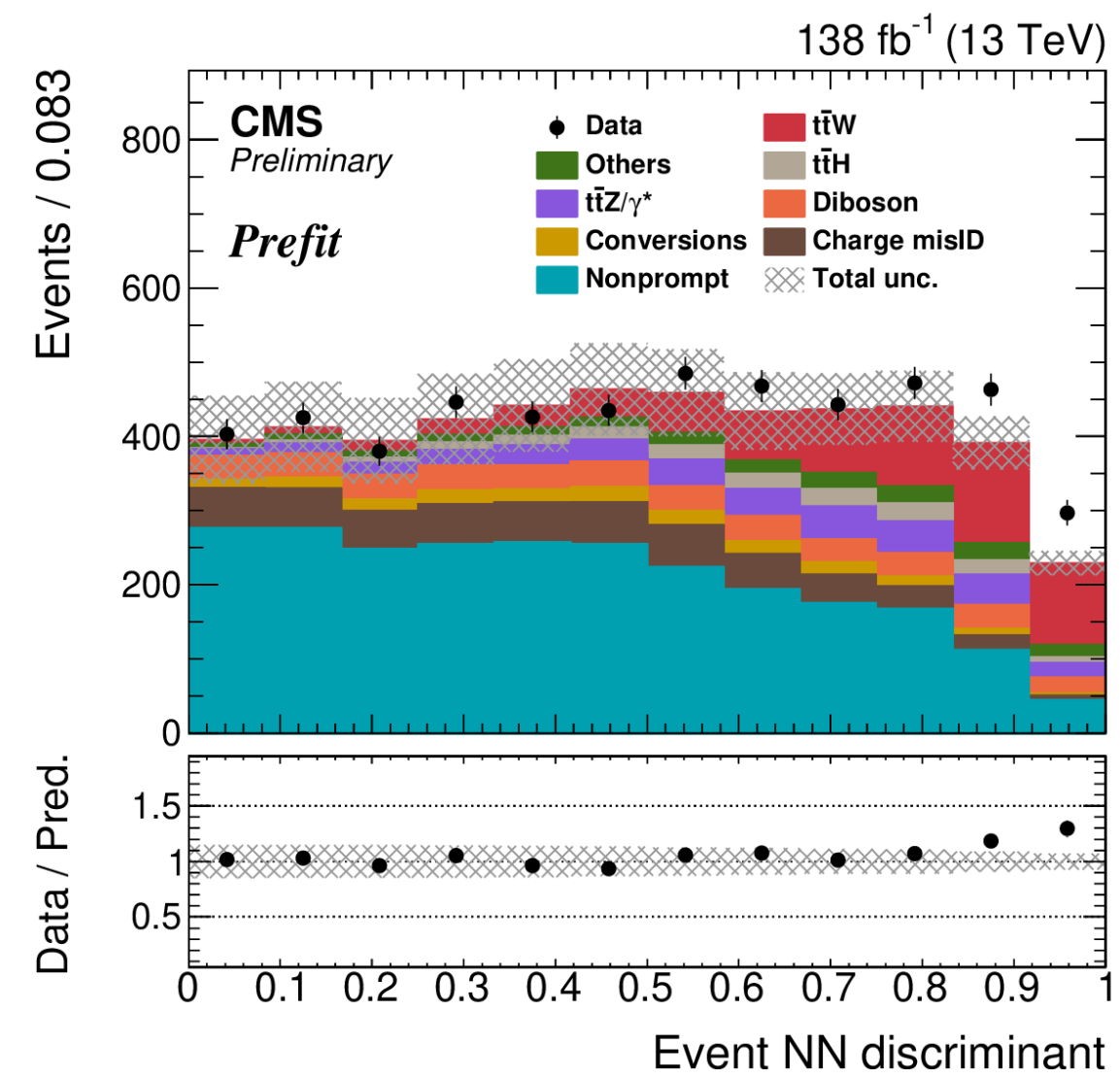
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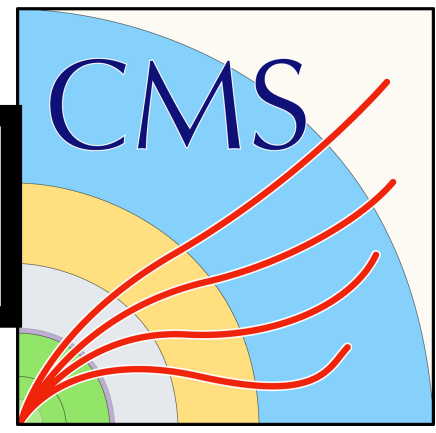
$\ell^+\ell^+$

$\ell^-\ell^-$

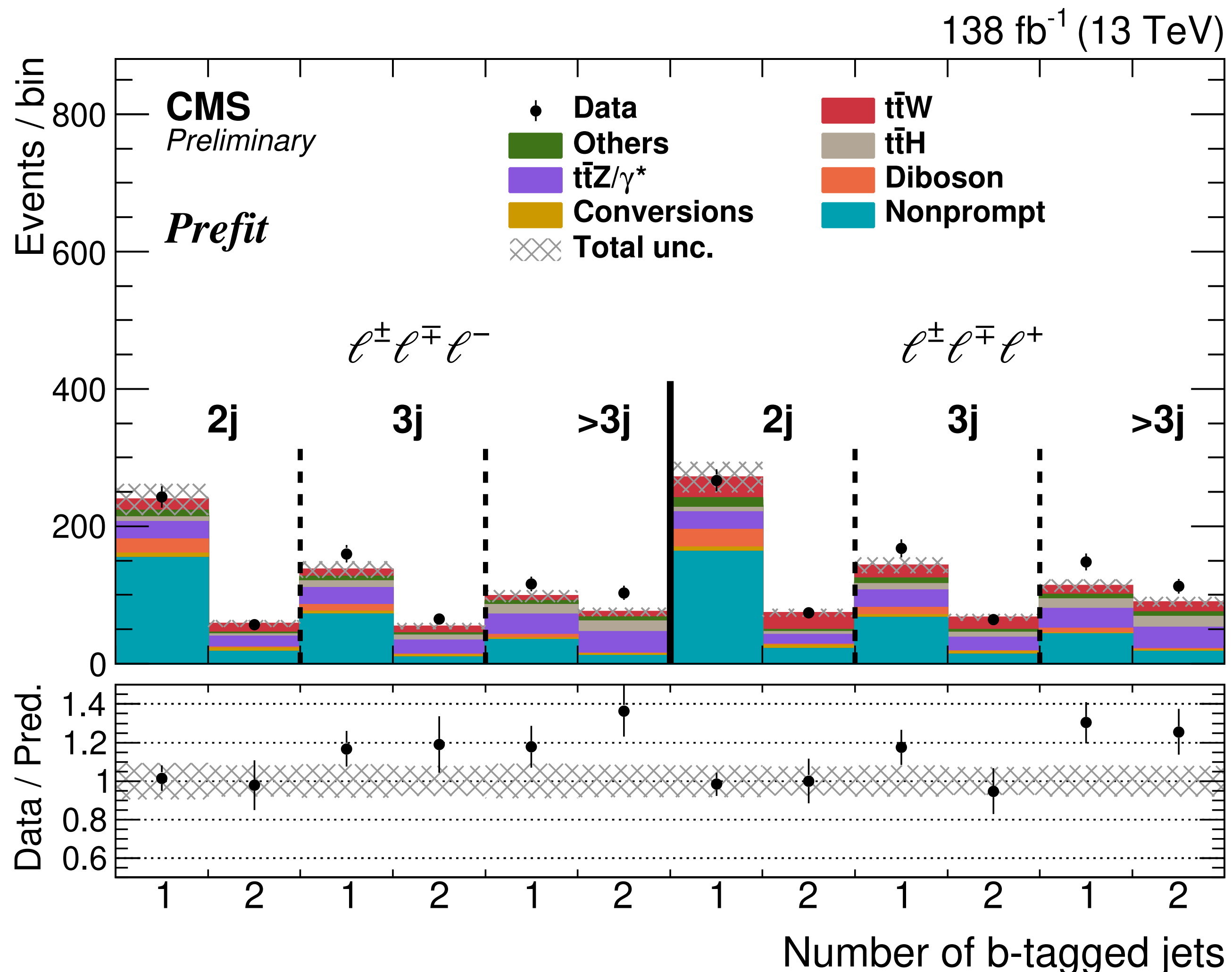


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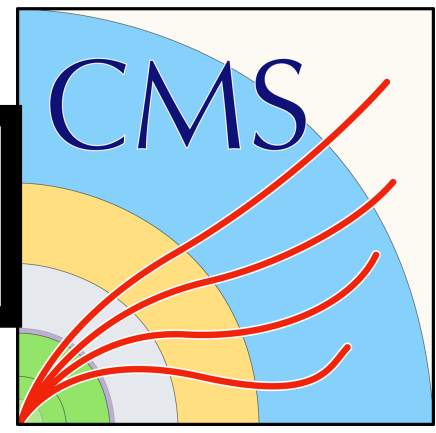
3-lepton signal region categories



$t\bar{t}W$ measurement from CMS

NEW

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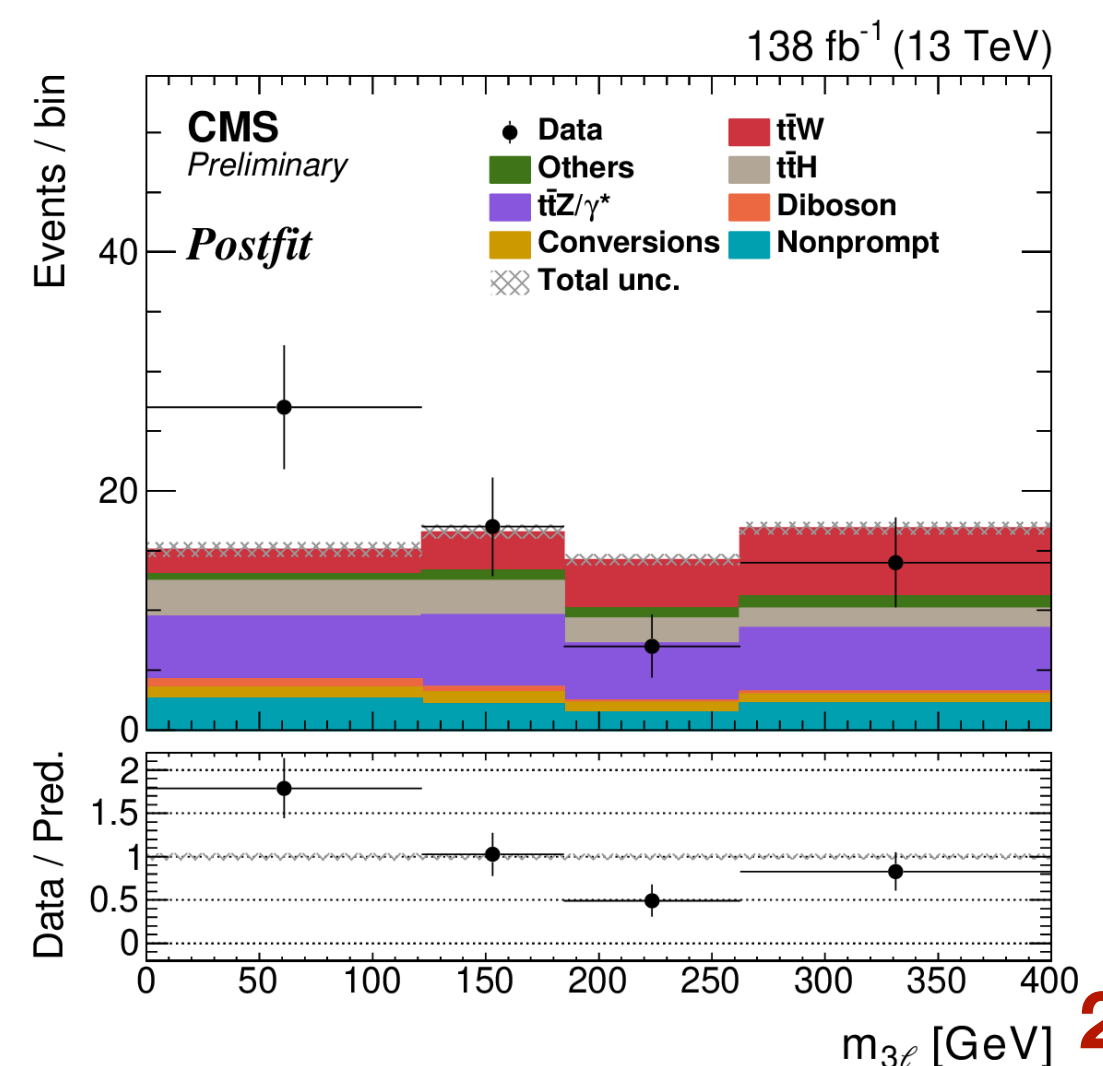
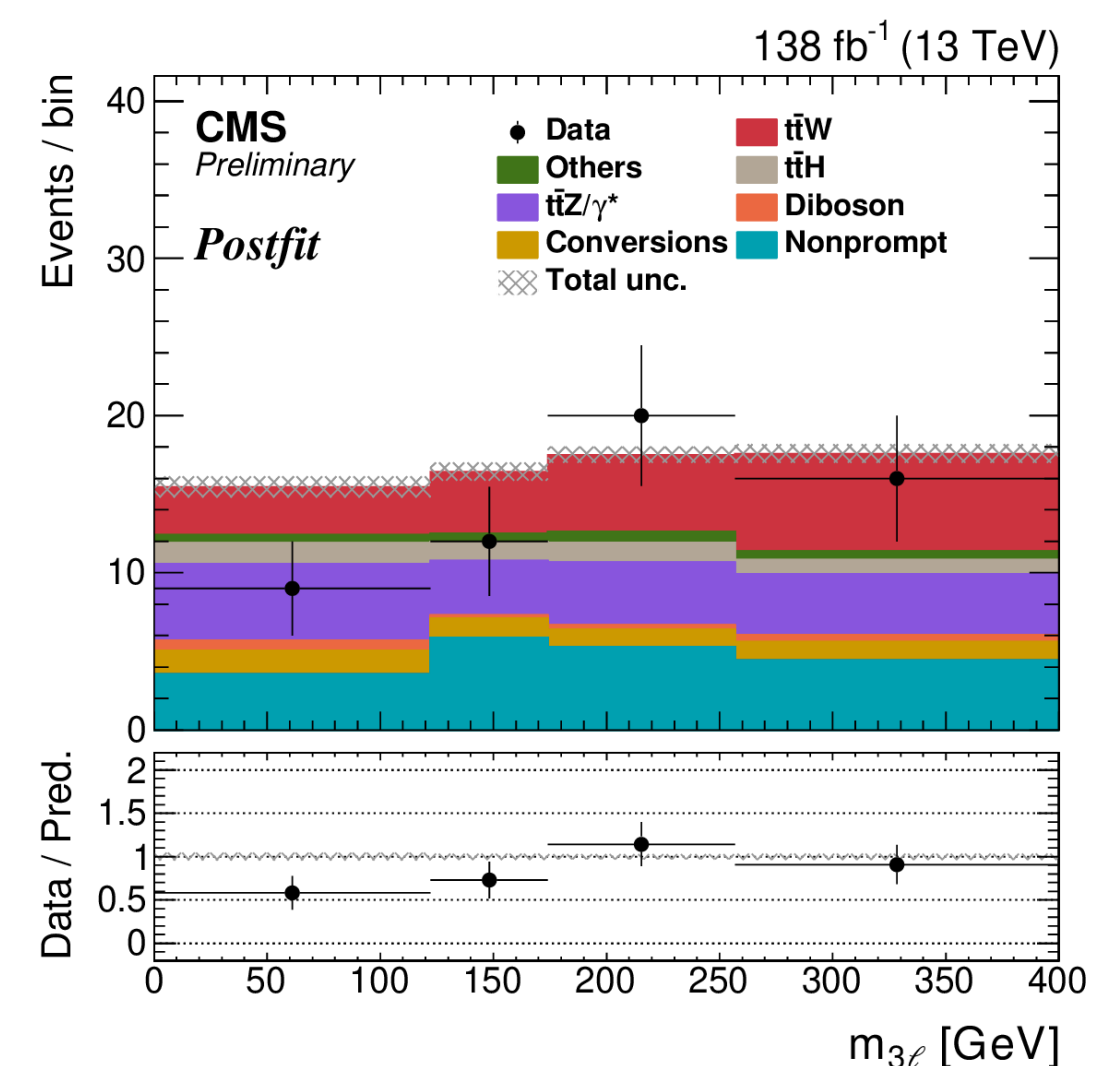
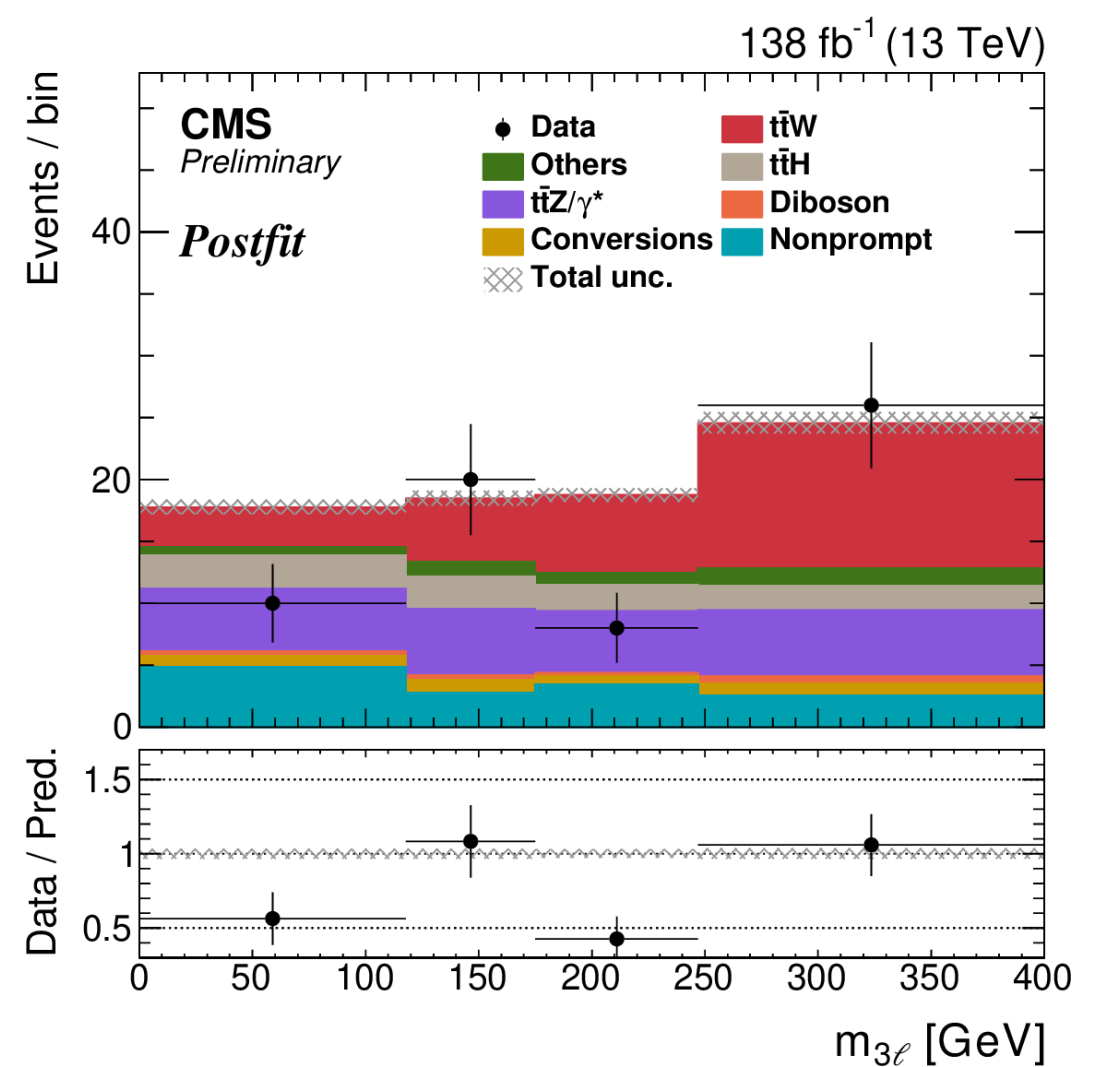
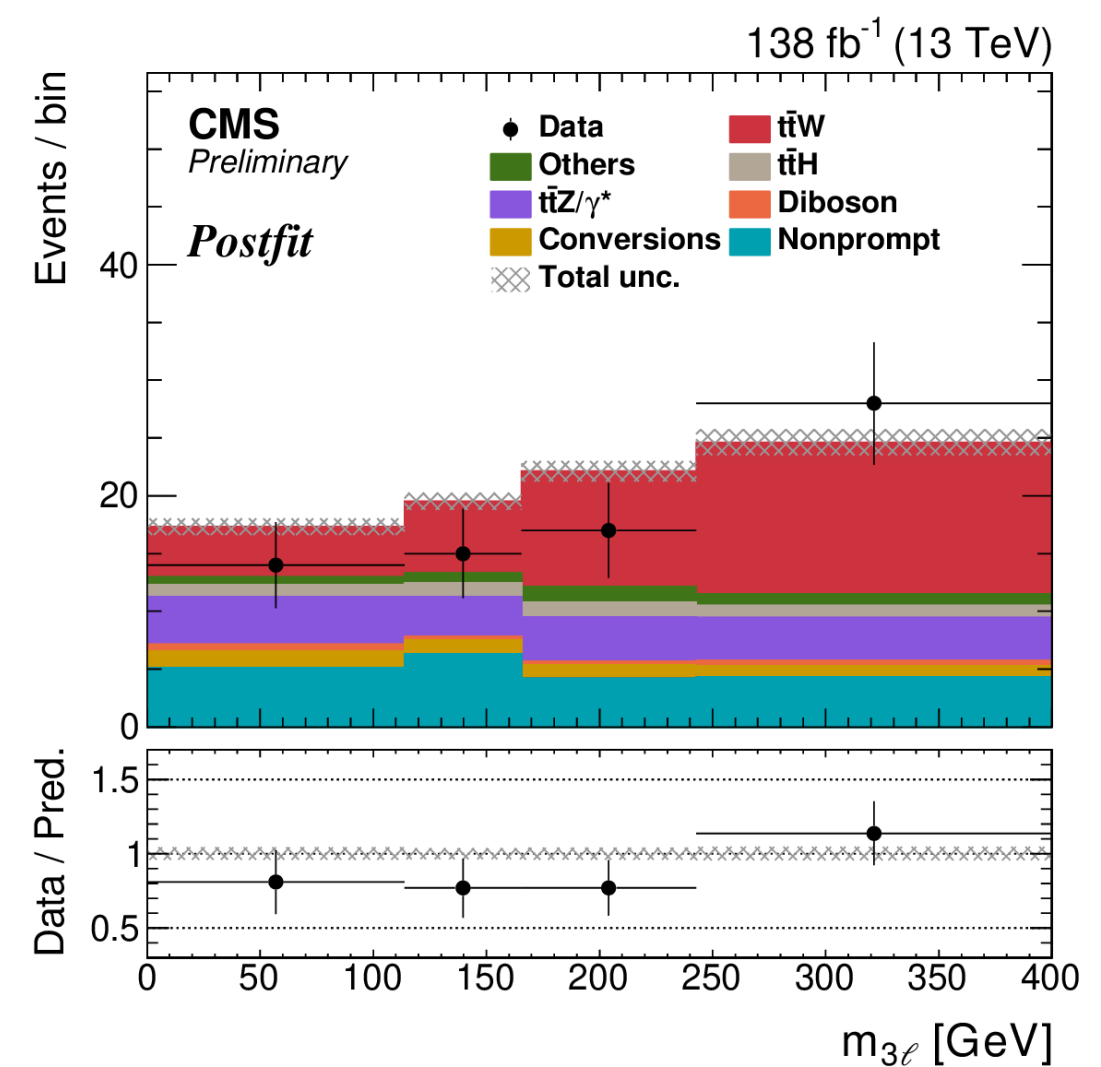
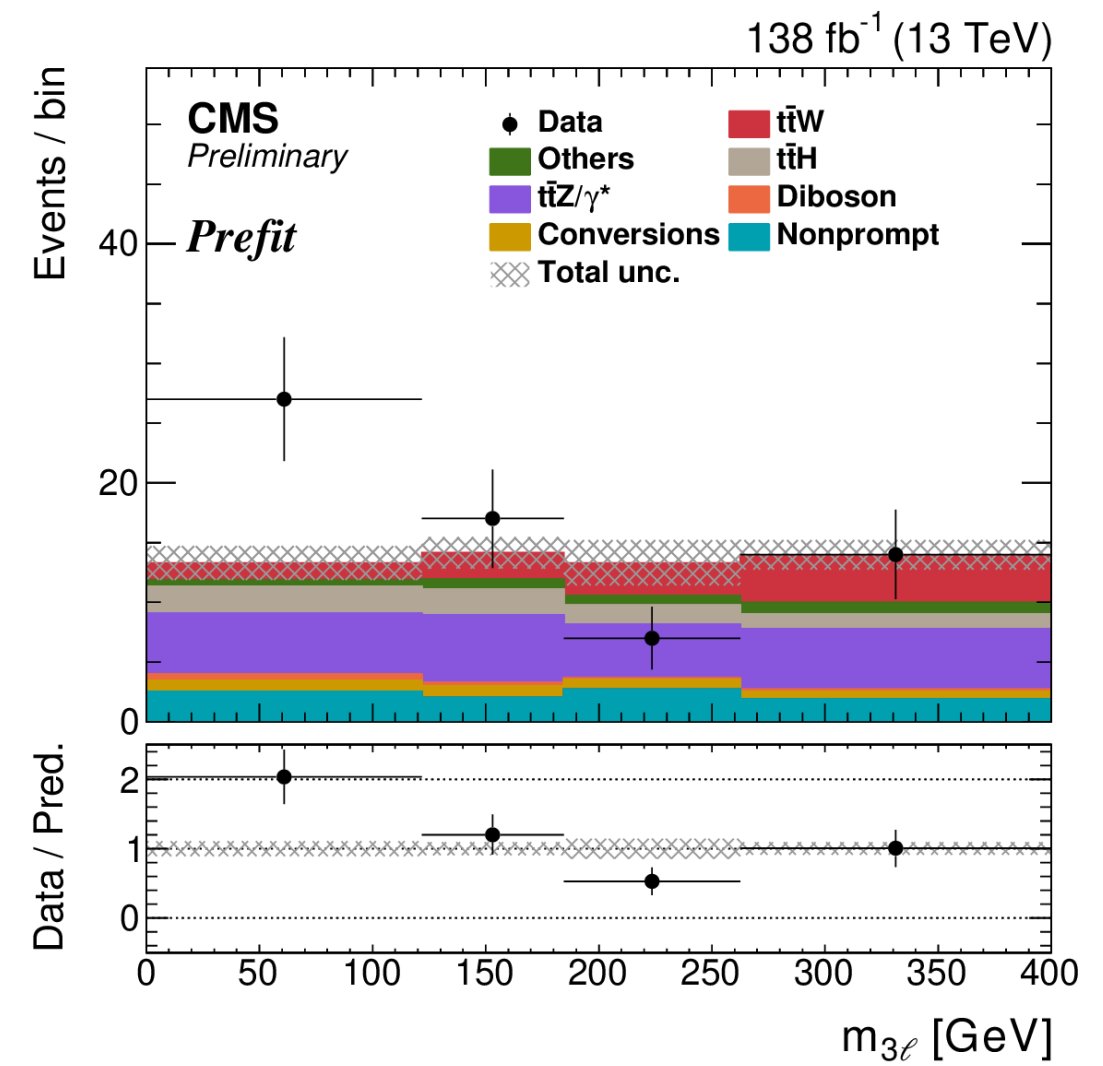
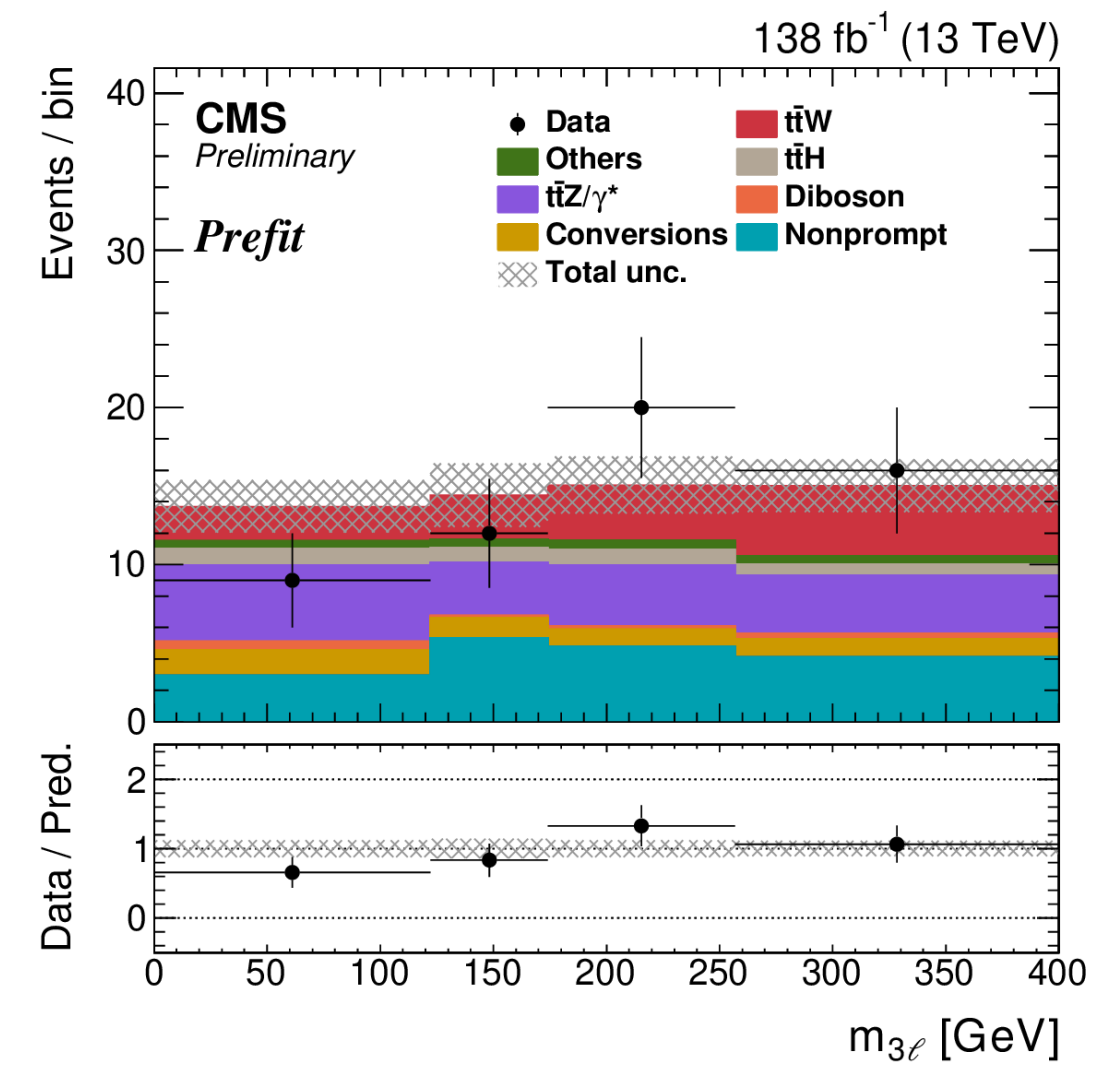
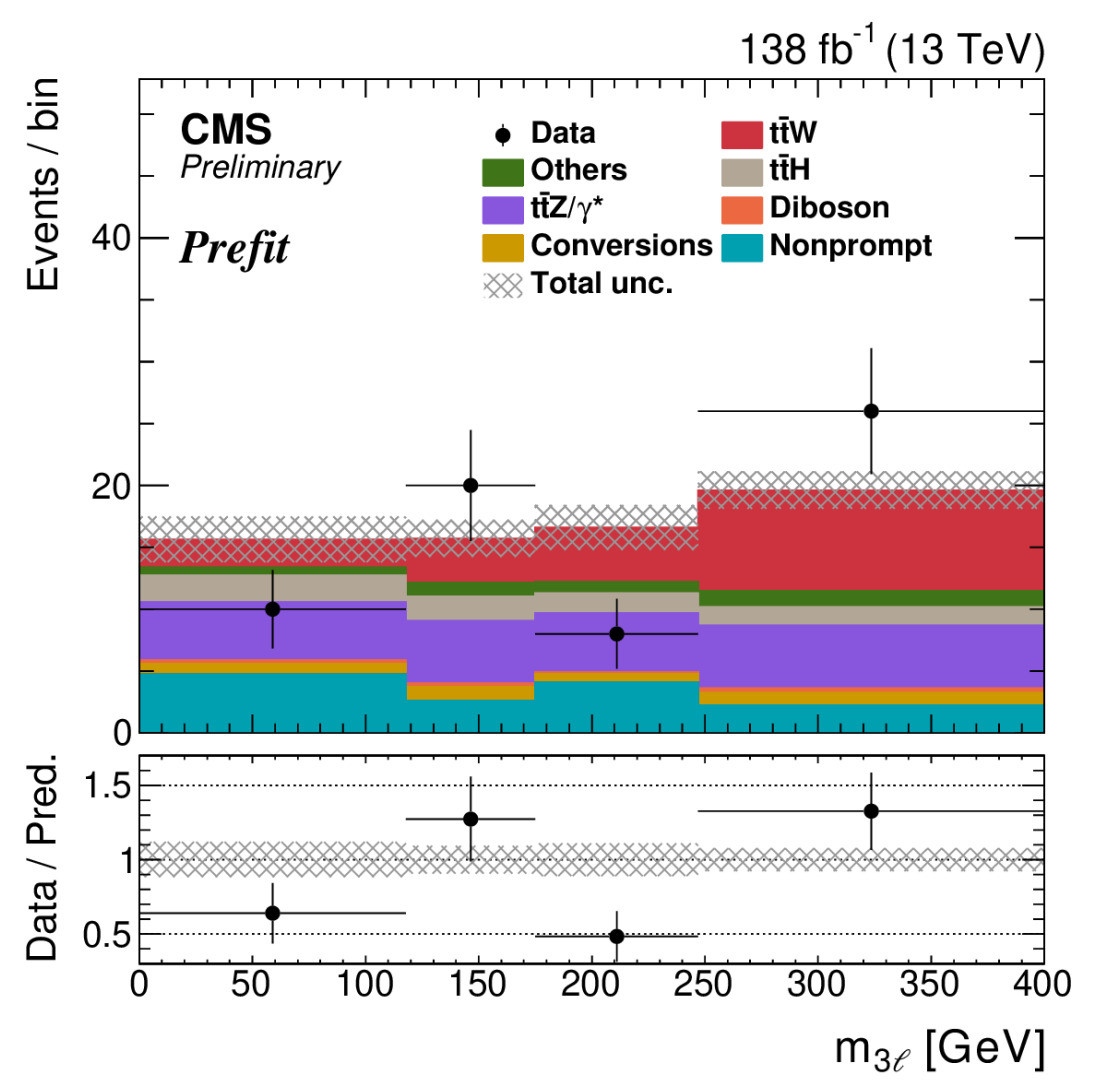
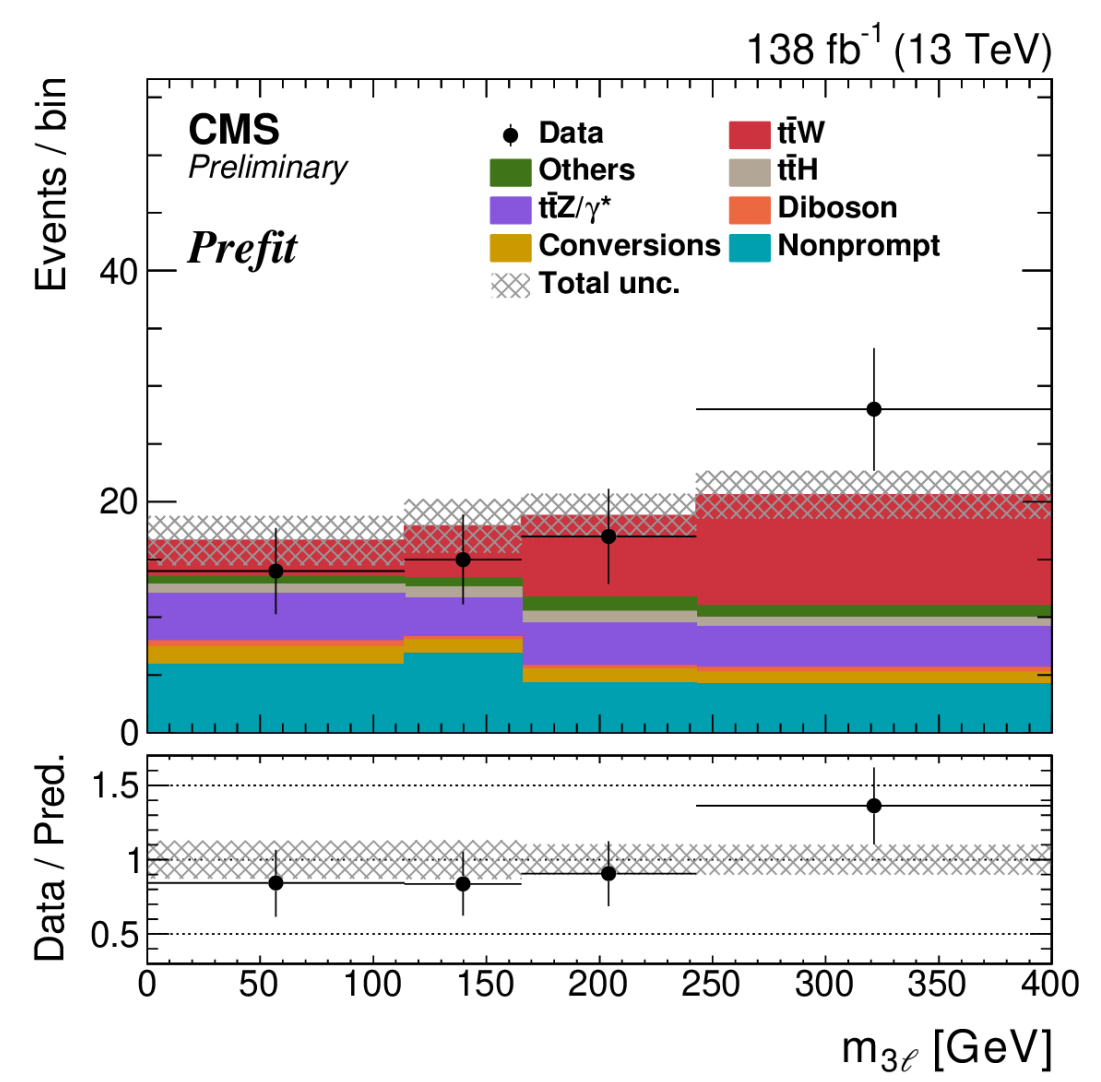


$\ell^\pm \ell^\pm \ell^+ 2j$

$\ell^\pm \ell^\pm \ell^+ \geq 3j$

$\ell^\pm \ell^\pm \ell^- 2j$

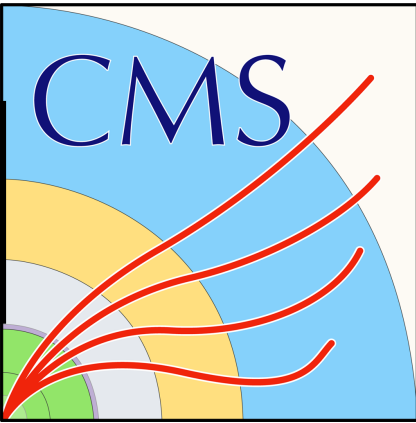
$\ell^\pm \ell^\pm \ell^- \geq 3j$



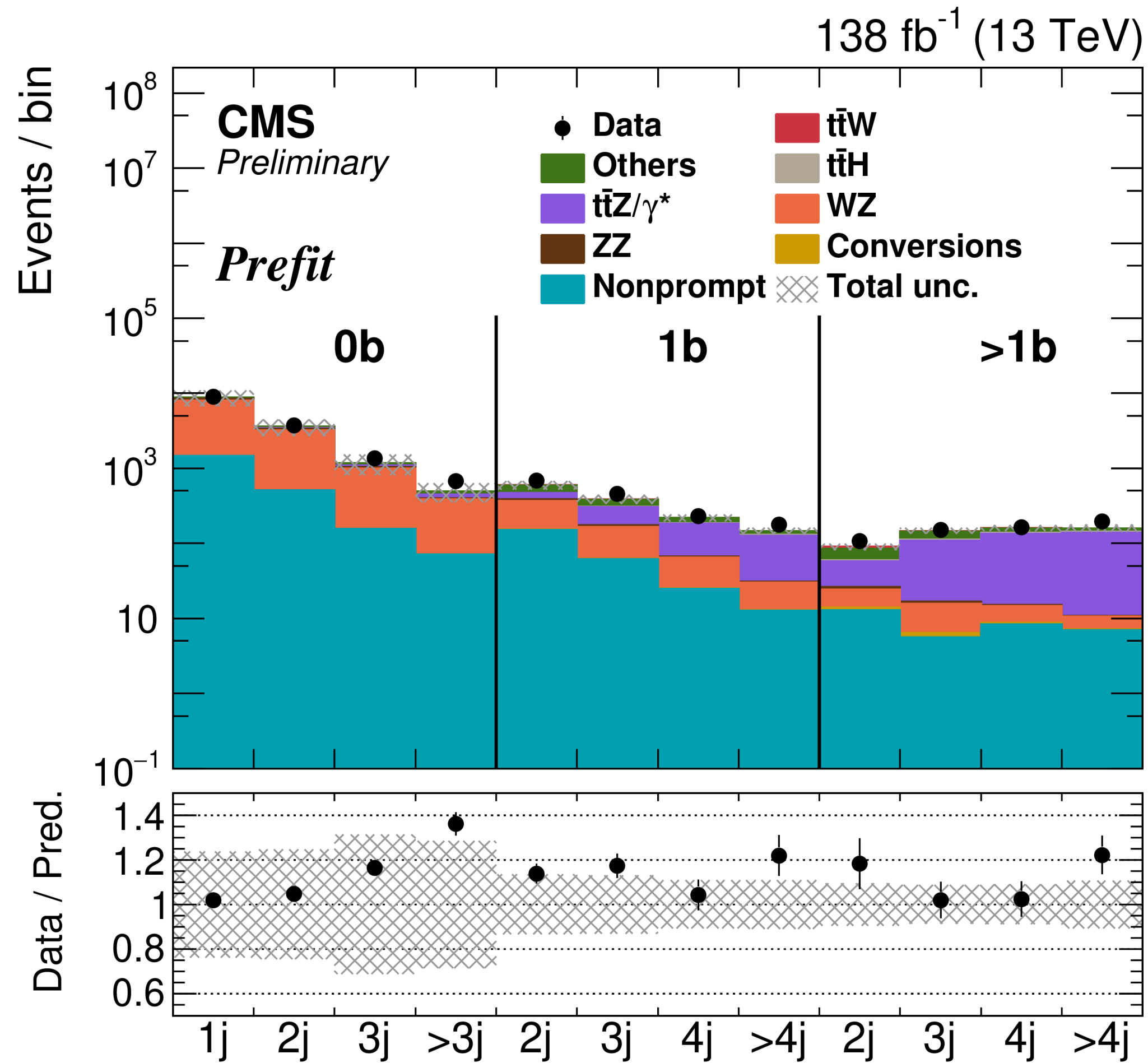
$t\bar{t}W$ measurement from CMS

NEW

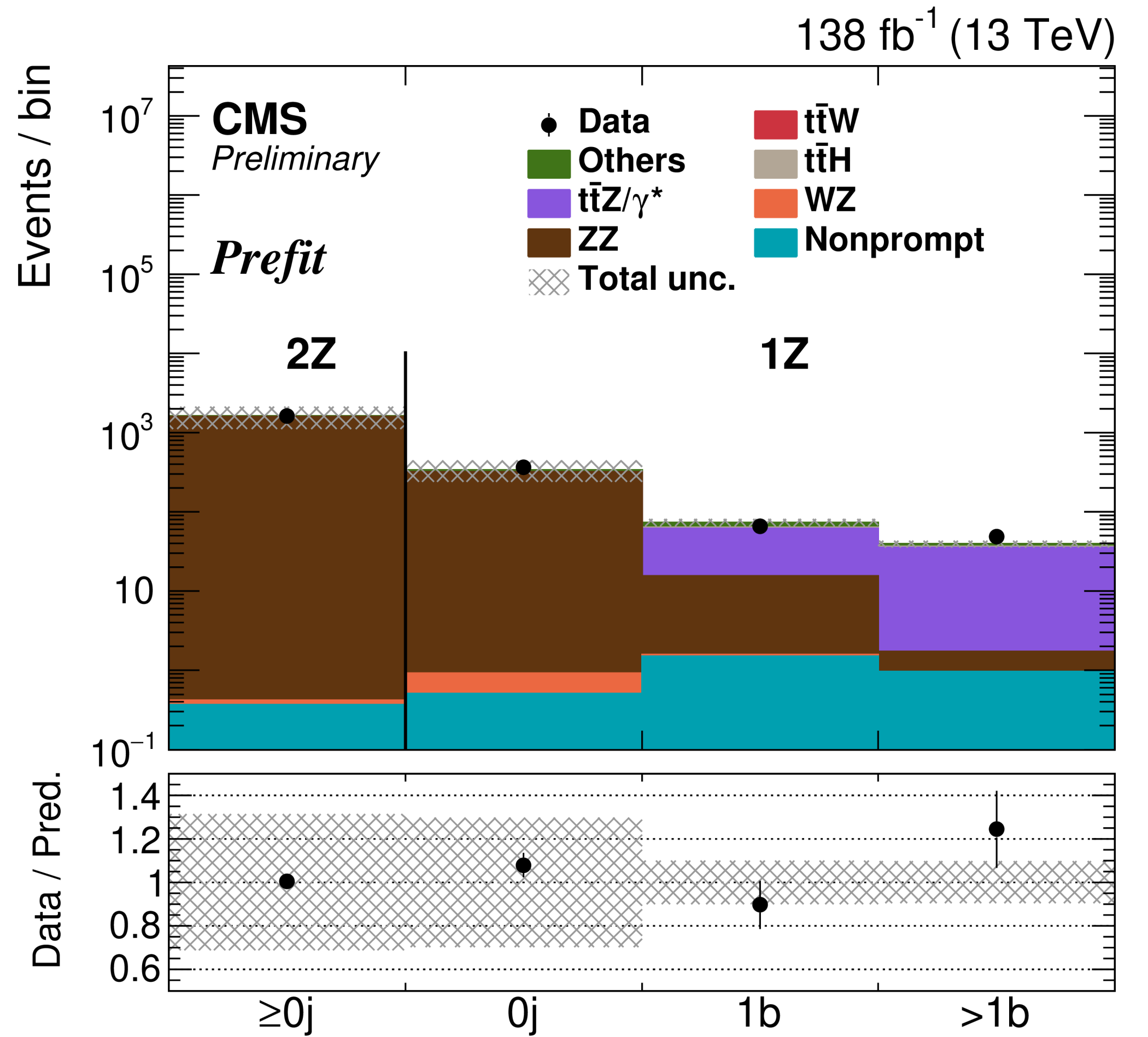
CMS-PAS-TOP-21-011



3-lepton control regions



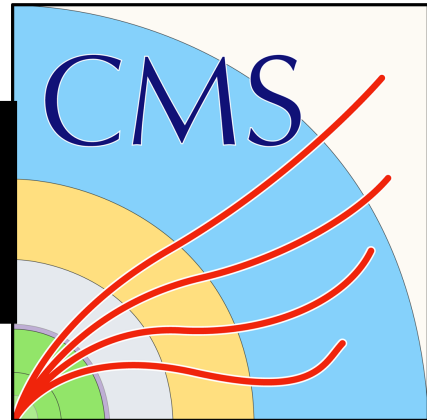
4-lepton control region



$t\bar{t}W$ measurement from CMS



CMS-PAS-TOP-21-011



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	l^+l^+	l^-l^-	$l^\pm l^\mp l^+$	$l^\pm l^\mp l^-$	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	

Boosted Z/H

Table 4: Major sources of uncertainty in the measurement of the signal strength modifiers $\mu_{t\bar{t}Z}$ and $\mu_{t\bar{t}H}$ for simulated Z or Higgs boson $p_T > 200$ GeV.

Source of uncertainty	$\Delta\mu_{t\bar{t}Z}$	$\Delta\mu_{t\bar{t}H}$
$t\bar{t} + c\bar{c}$ cross section	+0.24 -0.22	+0.17 -0.16
$t\bar{t} + b\bar{b}$ cross section	+0.17 -0.23	+0.15 -0.22
$t\bar{t} + 2b$ cross section	+0.03 -0.03	+0.10 -0.10
μ_R and μ_F scales	+0.19 -0.14	+0.10 -0.16
Parton shower	+0.15 -0.16	+0.06 -0.05
Top quark p_T modeling in $t\bar{t}$	+0.01 -0.01	+0.11 -0.13
b-tag efficiency	+0.25 -0.13	+0.10 -0.11
$b\bar{b}$ -tag efficiency	+0.17 -0.12	+0.04 -0.03
Jet energy scale and resolution	+0.11 -0.10	+0.11 -0.12
Jet mass scale and resolution	+0.10 -0.11	+0.08 -0.08

Table 5: Observed (median expected ± 1 standard deviation) 95% CL upper limits for $t\bar{t}Z$ and $t\bar{t}H$ differential cross sections.

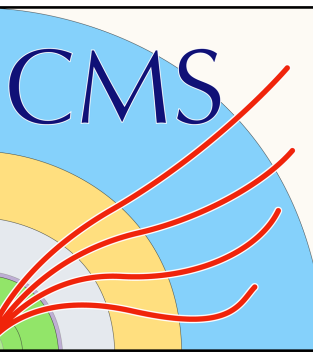
Signal	$p_T^{Z/H}$ (GeV) interval	95% CL upper limit (fb)	95% CL upper limit / SM
$t\bar{t}Z$	(200, 300]	359 (492 ⁺²¹⁶ ₋₁₄₃)	3.42 (4.69 ^{+2.06} _{-1.36})
	(300, 450]	208 (135 ⁺⁵⁸ ₋₃₉)	4.88 (3.17 ^{+1.37} _{-0.91})
	(450, ∞)	49.1 (50.7 ^{+23.0} _{-15.4})	4.02 (4.16 ^{+1.89} _{-1.26})
$t\bar{t}H$	(200, 300]	418 (736 ⁺²⁹⁶ ₋₂₁₀)	8.02 (14.1 ^{+5.7} _{-4.0})
	(300, 450]	59.9 (47.3 ^{+20.5} _{-13.9})	3.24 (2.55 ^{+1.11} _{-0.75})
	(450, ∞)	9.78 (16.5 ^{+7.4} _{-4.9})	1.96 (3.30 ^{+1.49} _{-0.98})

Signal strength	Observed $\pm 1\sigma$	Stat.	MC Stat.	Experiment	Theory	Expected $\pm 1\sigma$
$\mu_{t\bar{t}Z}$	0.65 ^{+1.05} _{-0.98}	+0.80 -0.76	+0.37 -0.38	+0.38 -0.31	+0.42 -0.38	1.00 ^{+0.92} _{-0.84}
$\mu_{t\bar{t}H}$	-0.33 ^{+0.87} _{-0.85}	+0.72 -0.65	+0.32 -0.34	+0.19 -0.17	+0.30 -0.38	1.00 ^{+0.79} _{-0.73}

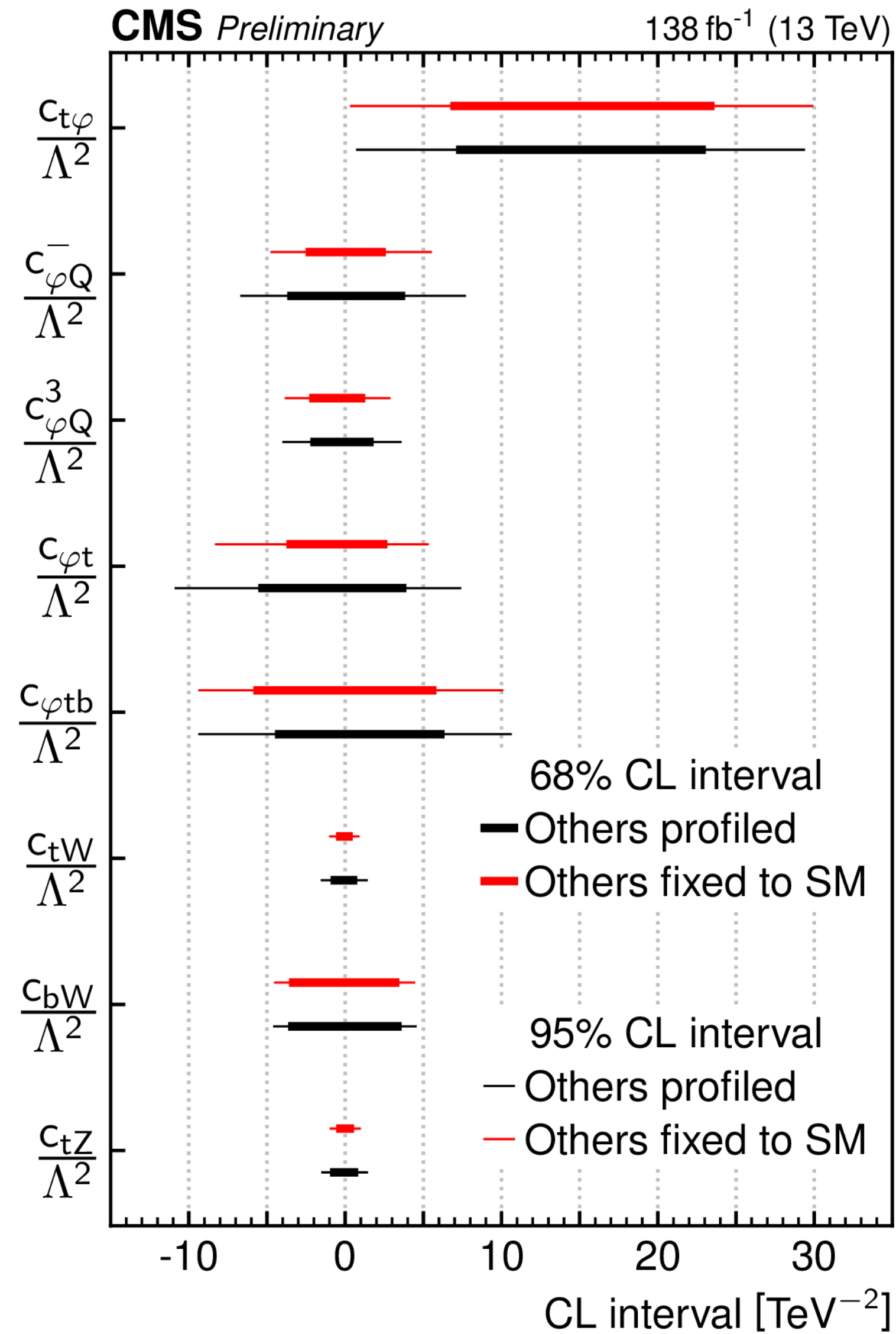
$t\bar{t}Z$ measurements

NEW

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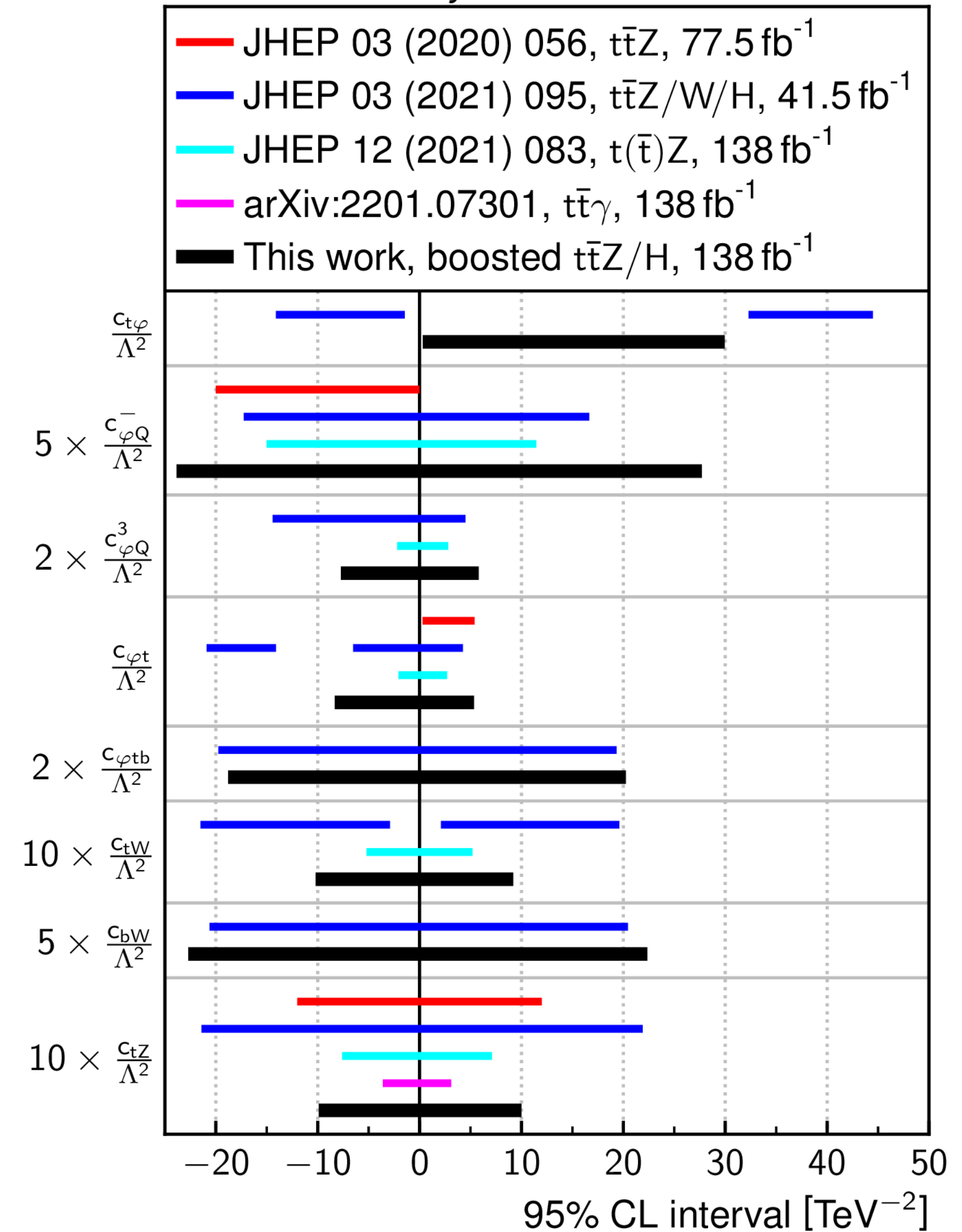


Boosted Z/H



CMS Preliminary

13 TeV

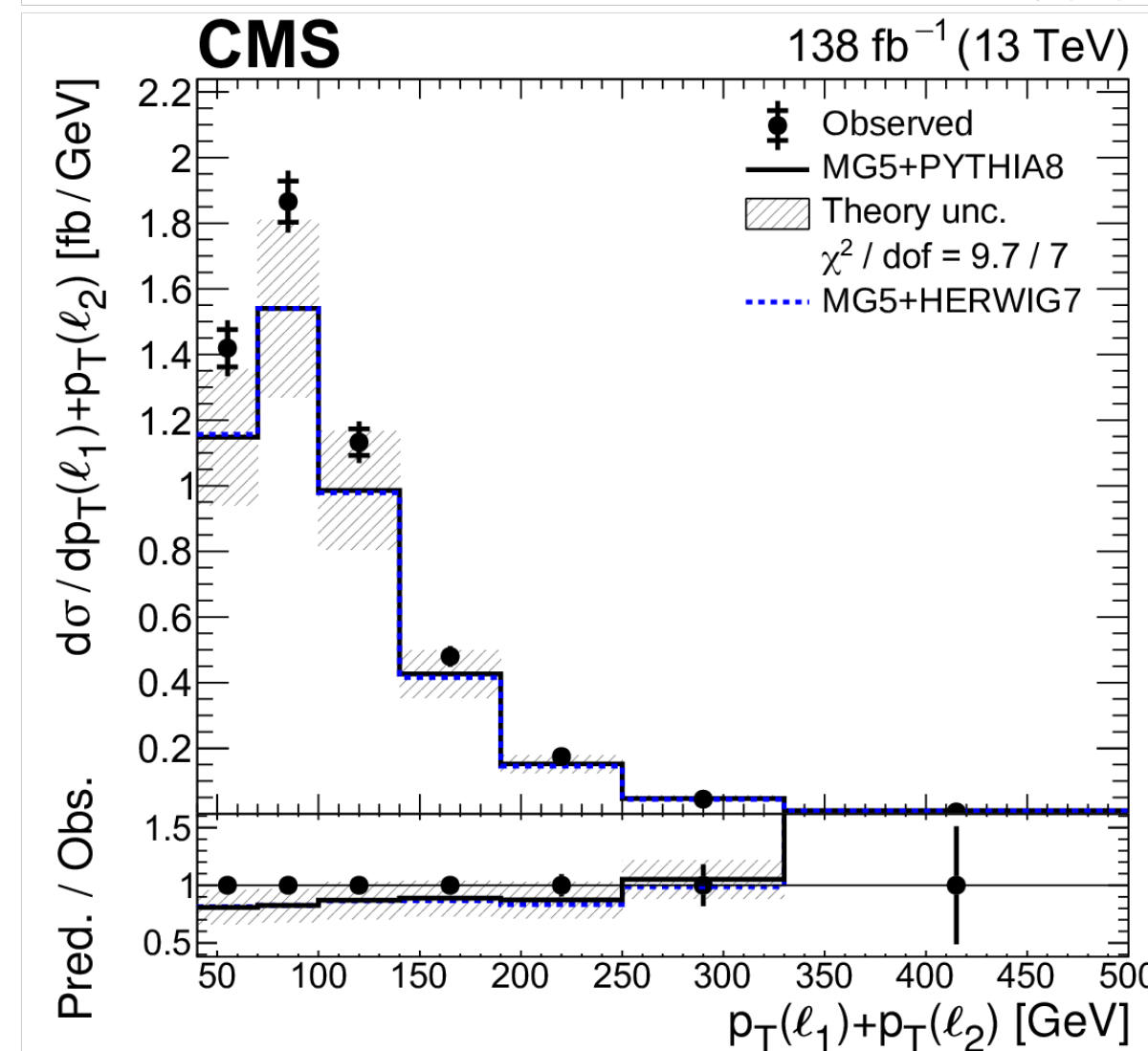
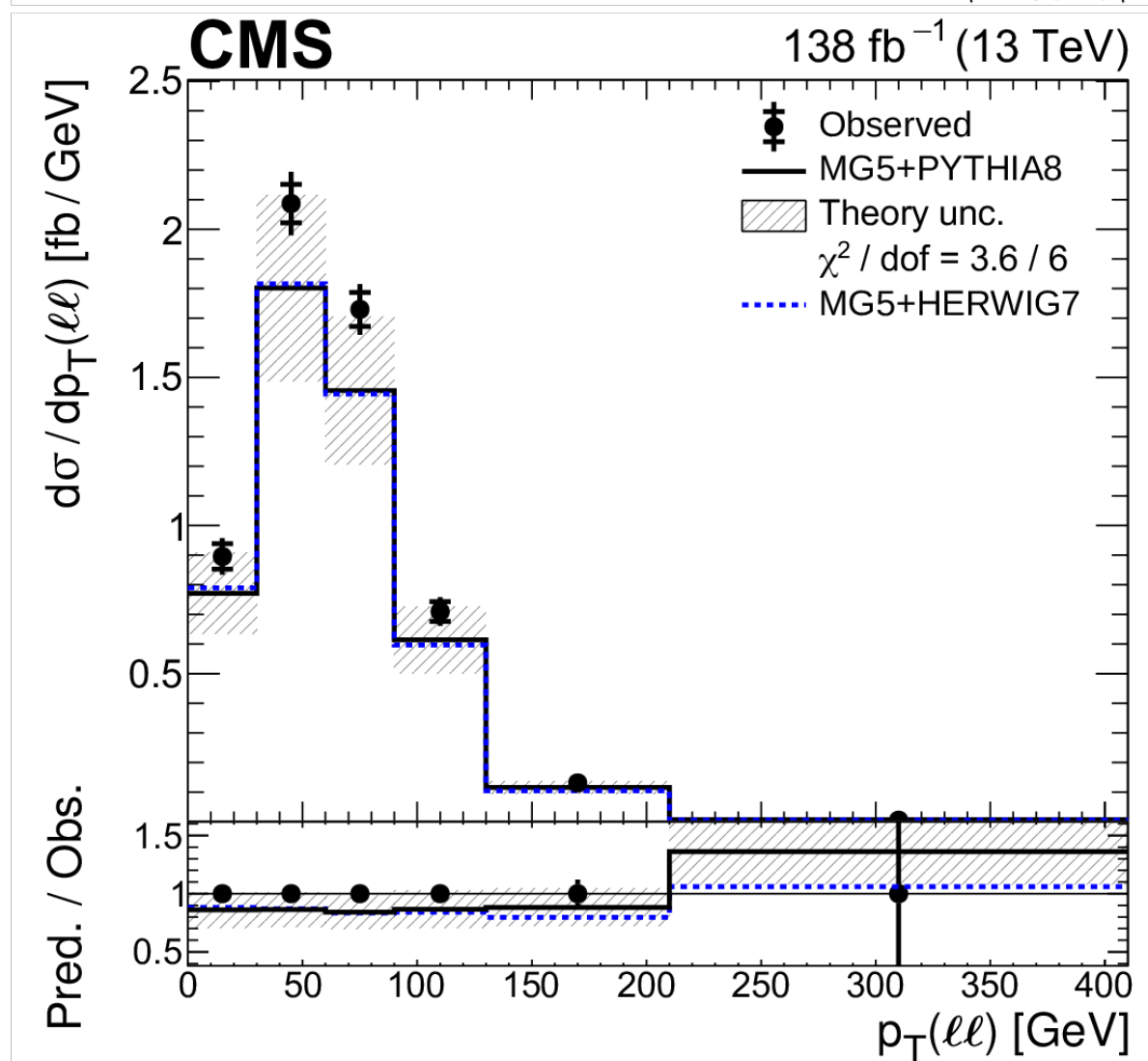
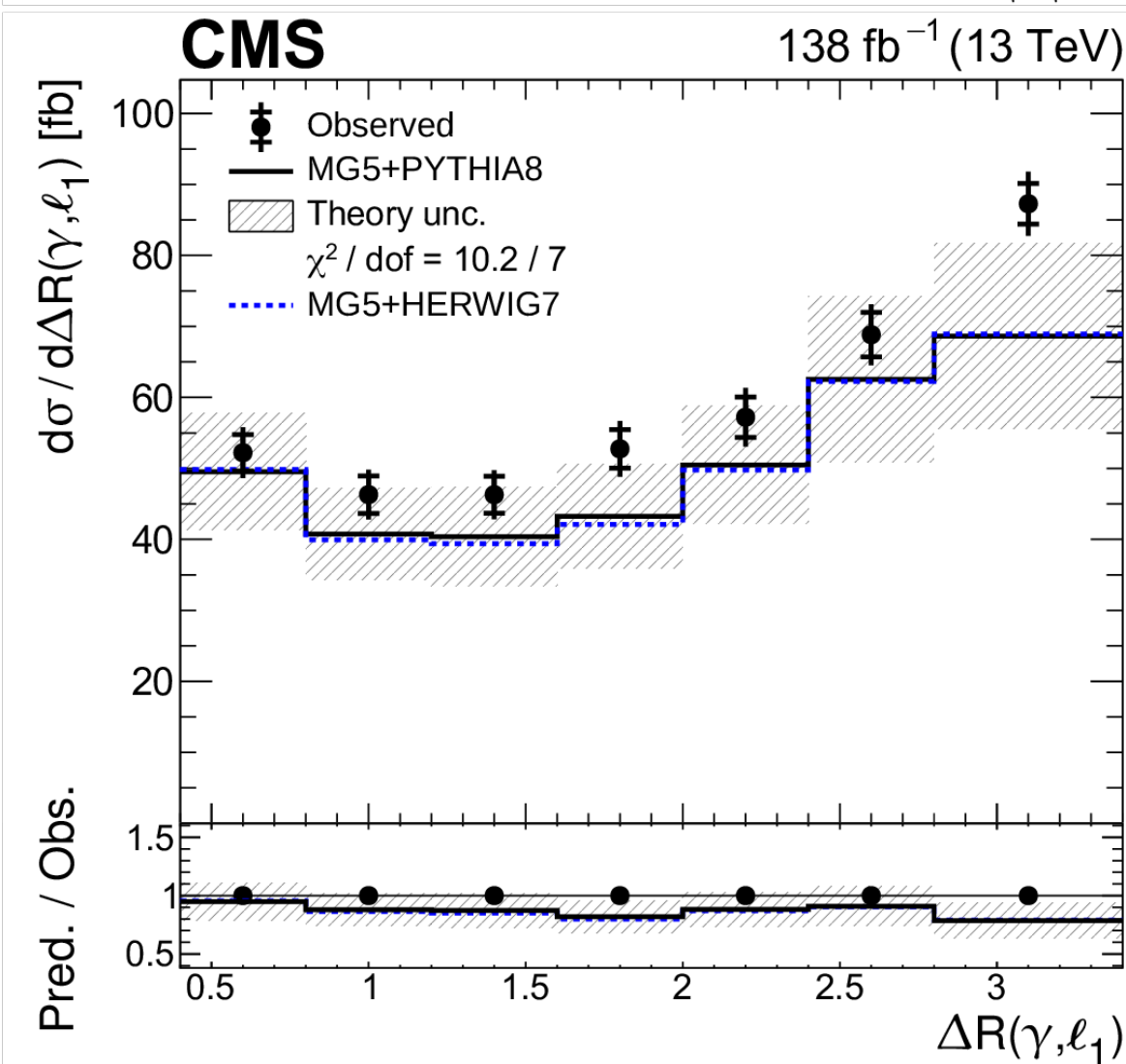
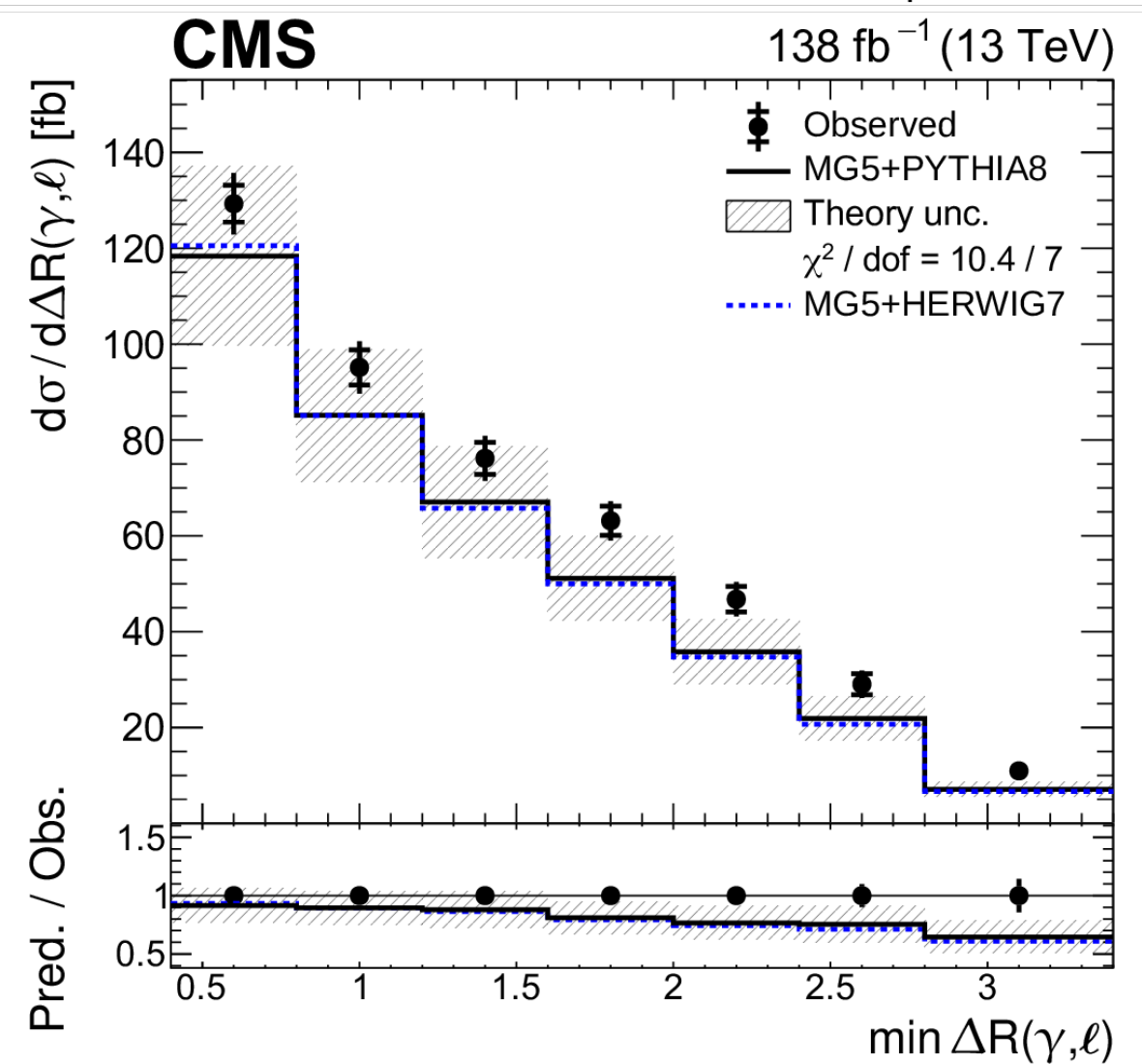
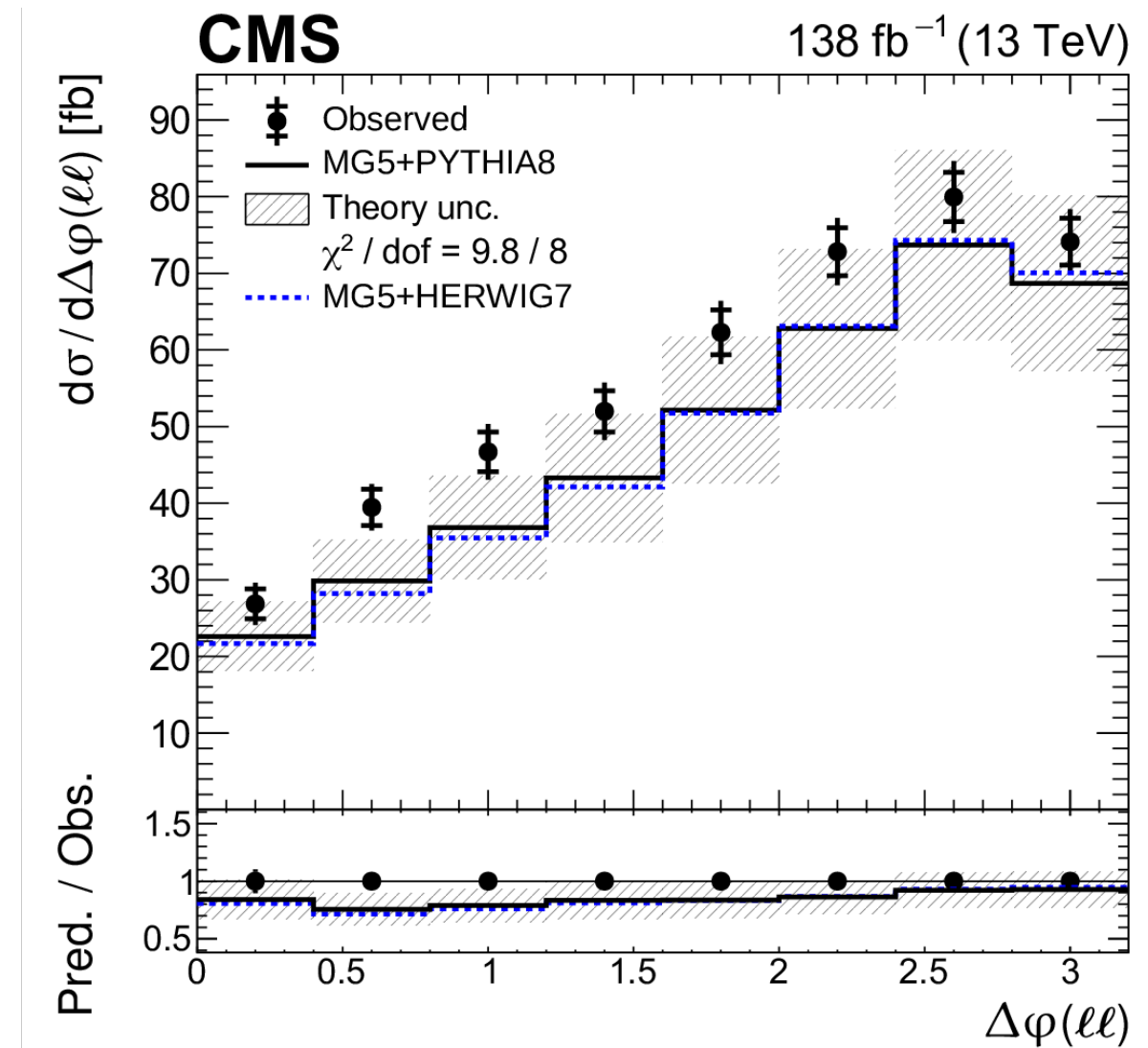
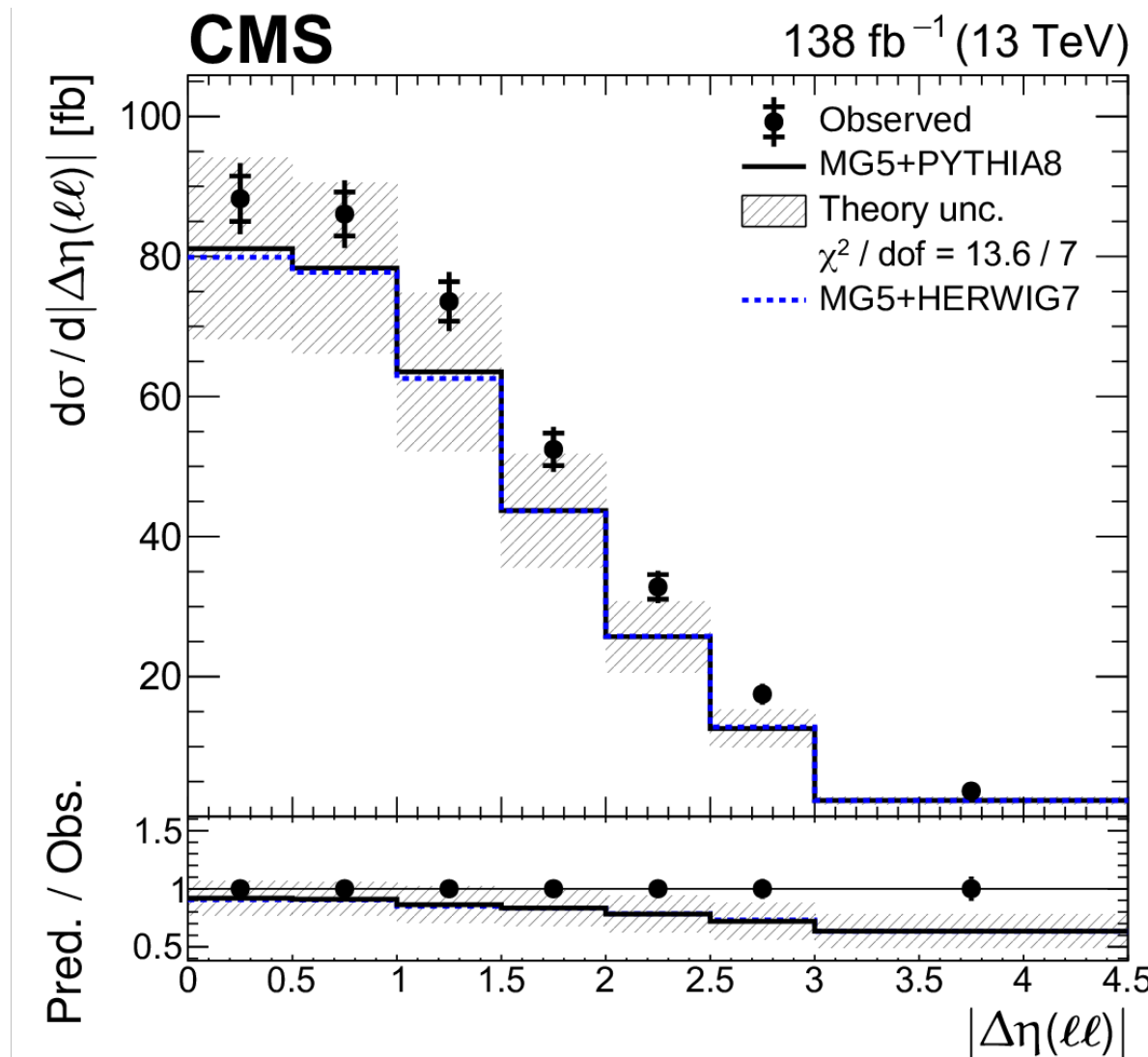
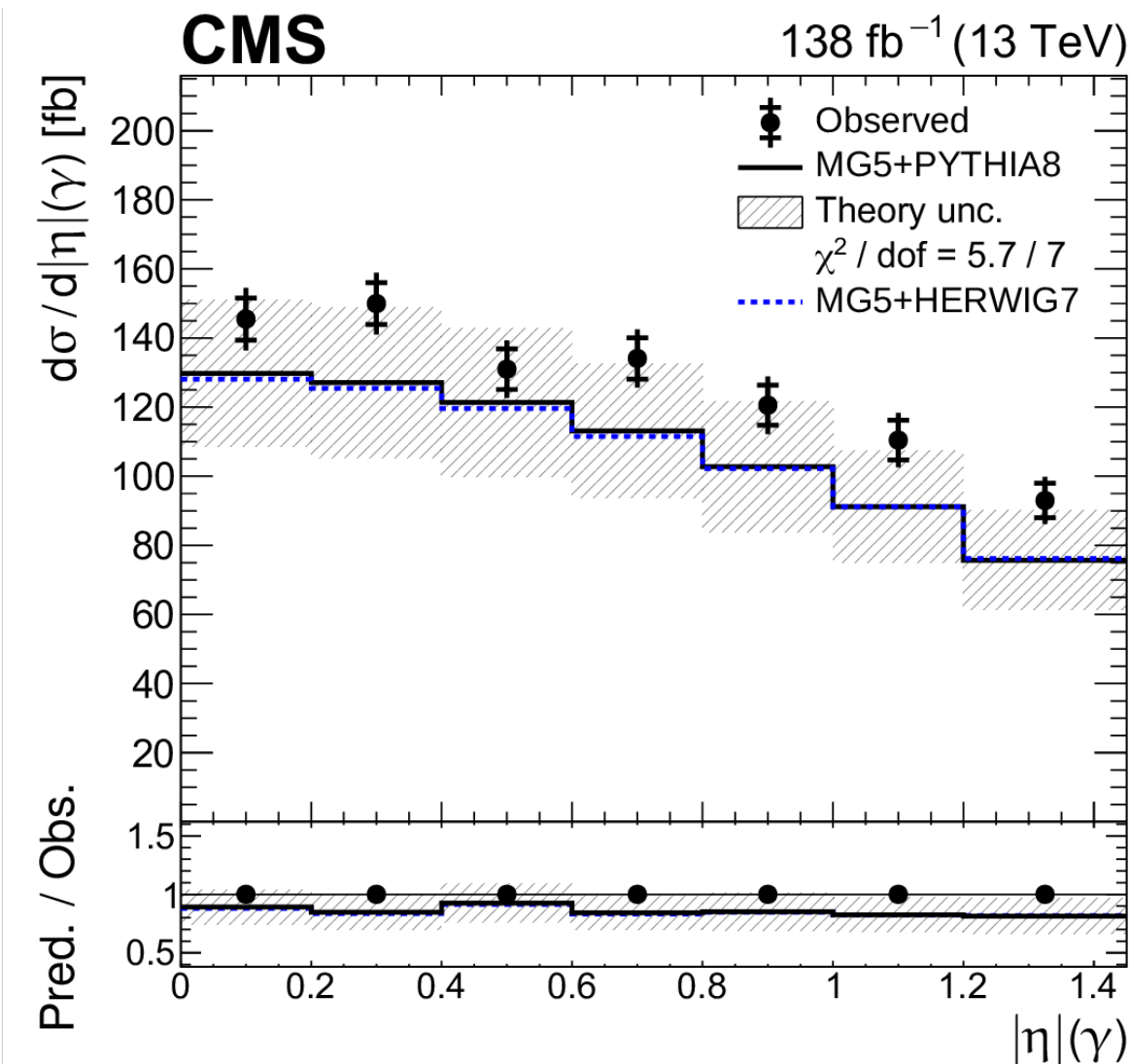
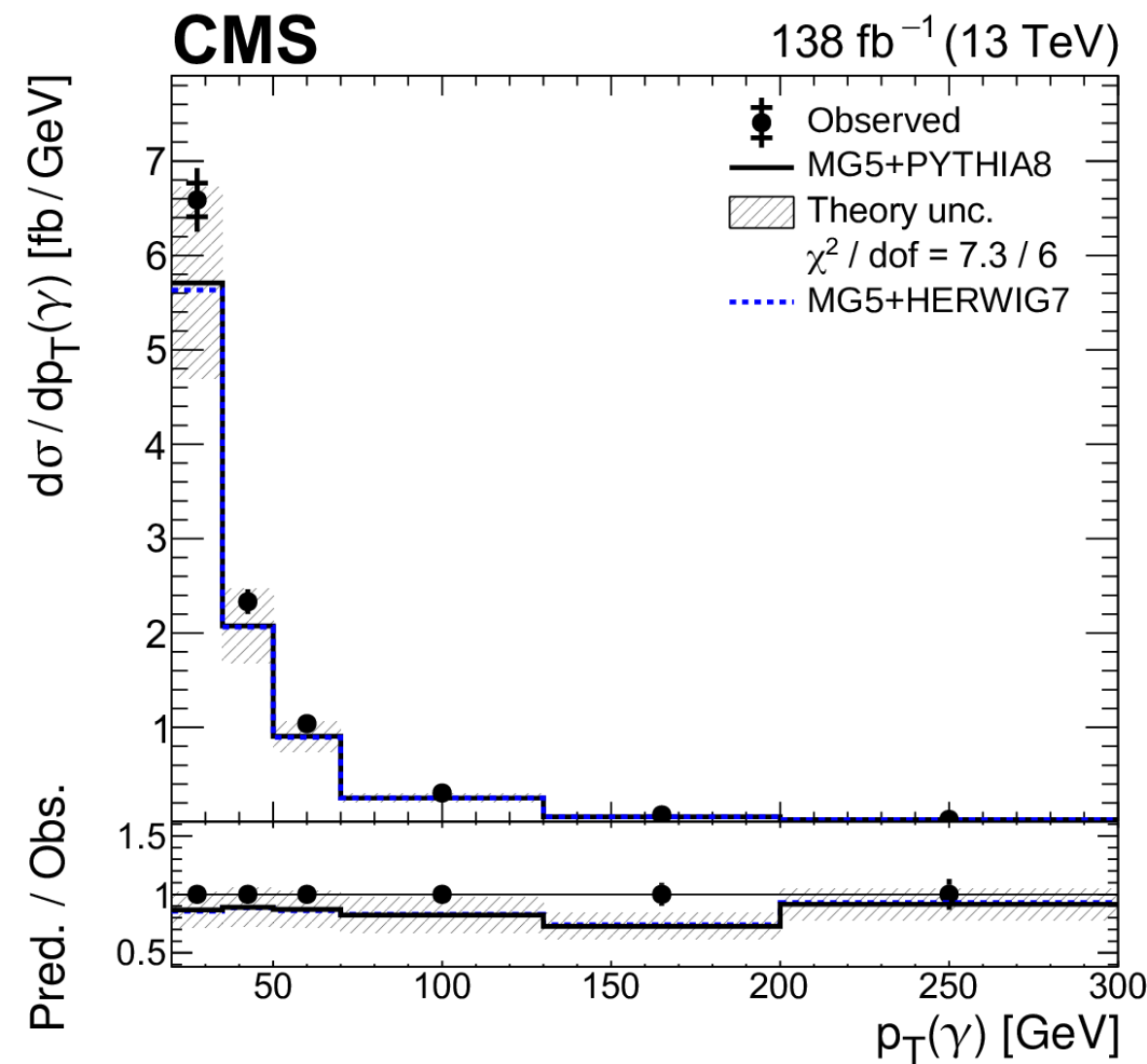
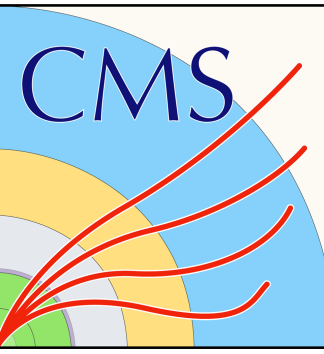


$t\bar{t}\gamma$ measurements

Differential cross-sections

CMS-TOP-21-004

NEW

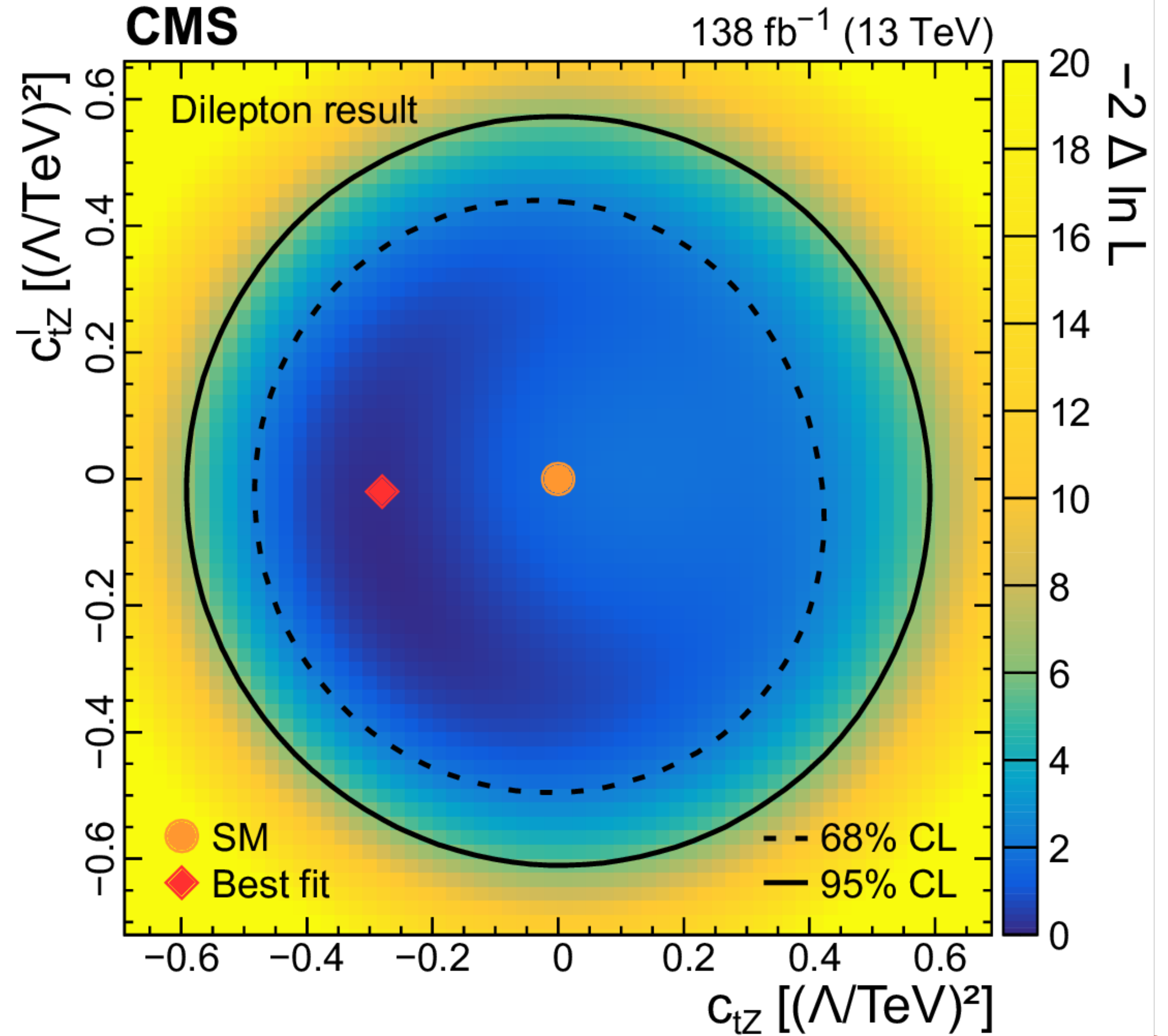
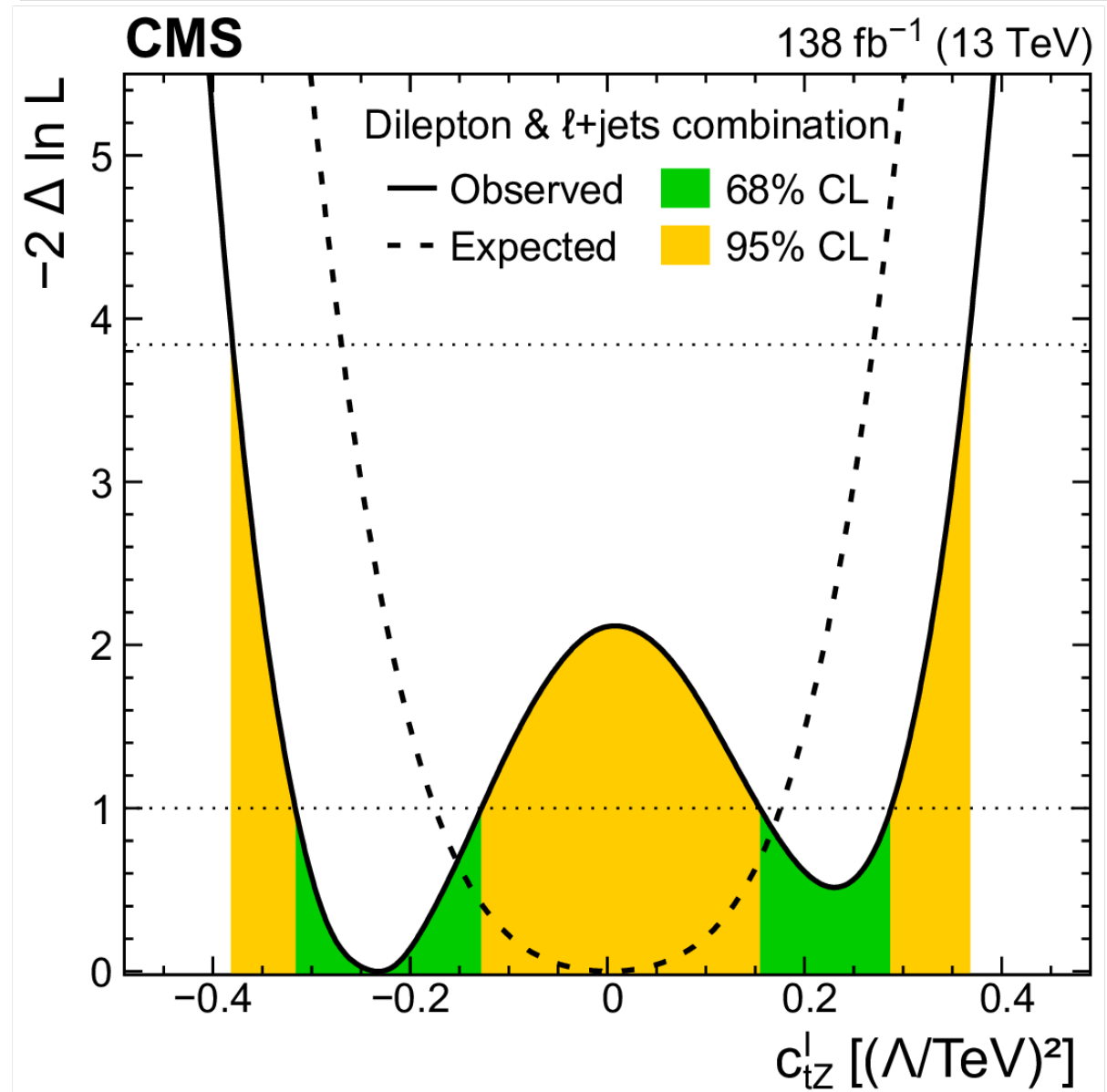
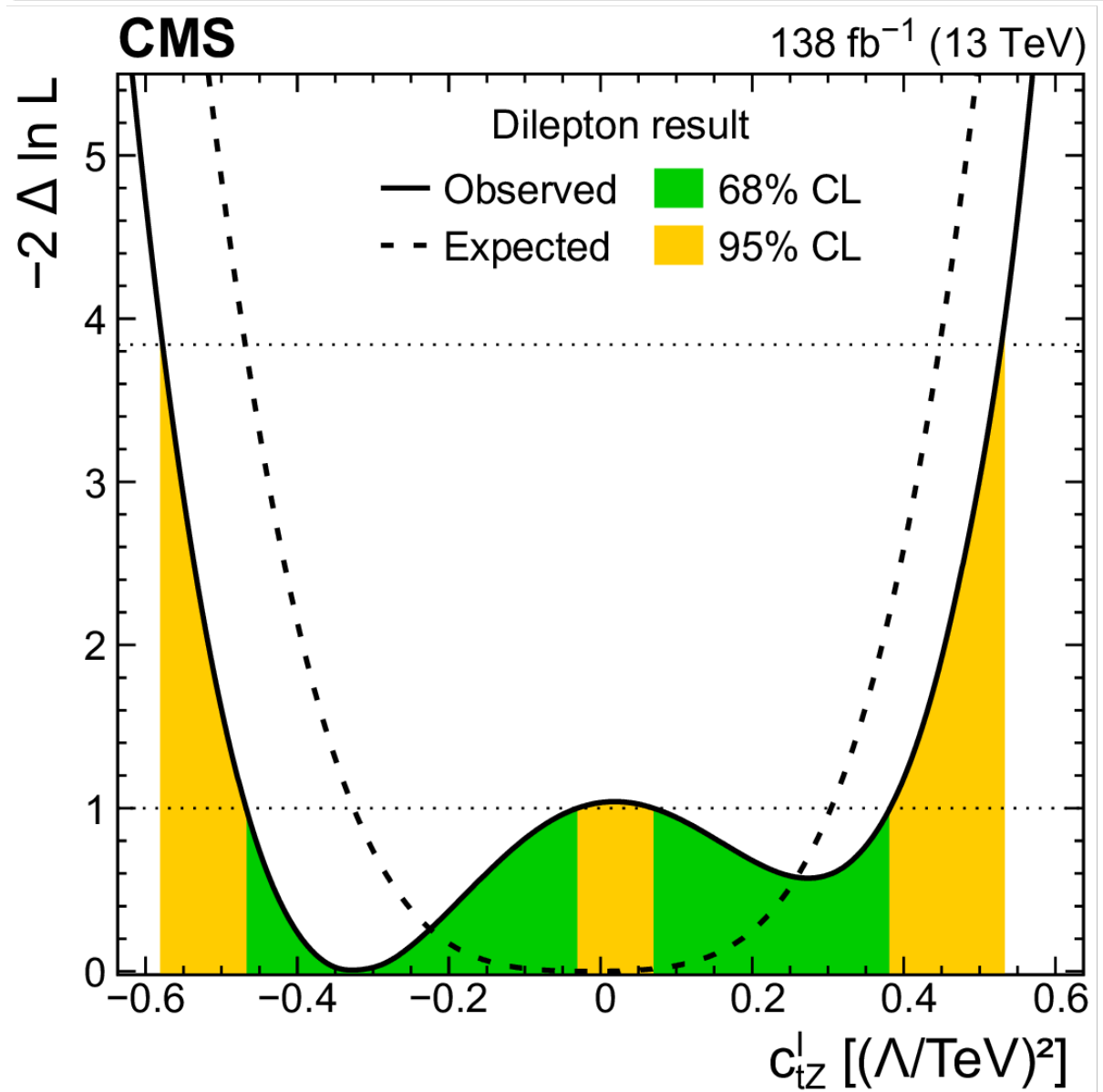
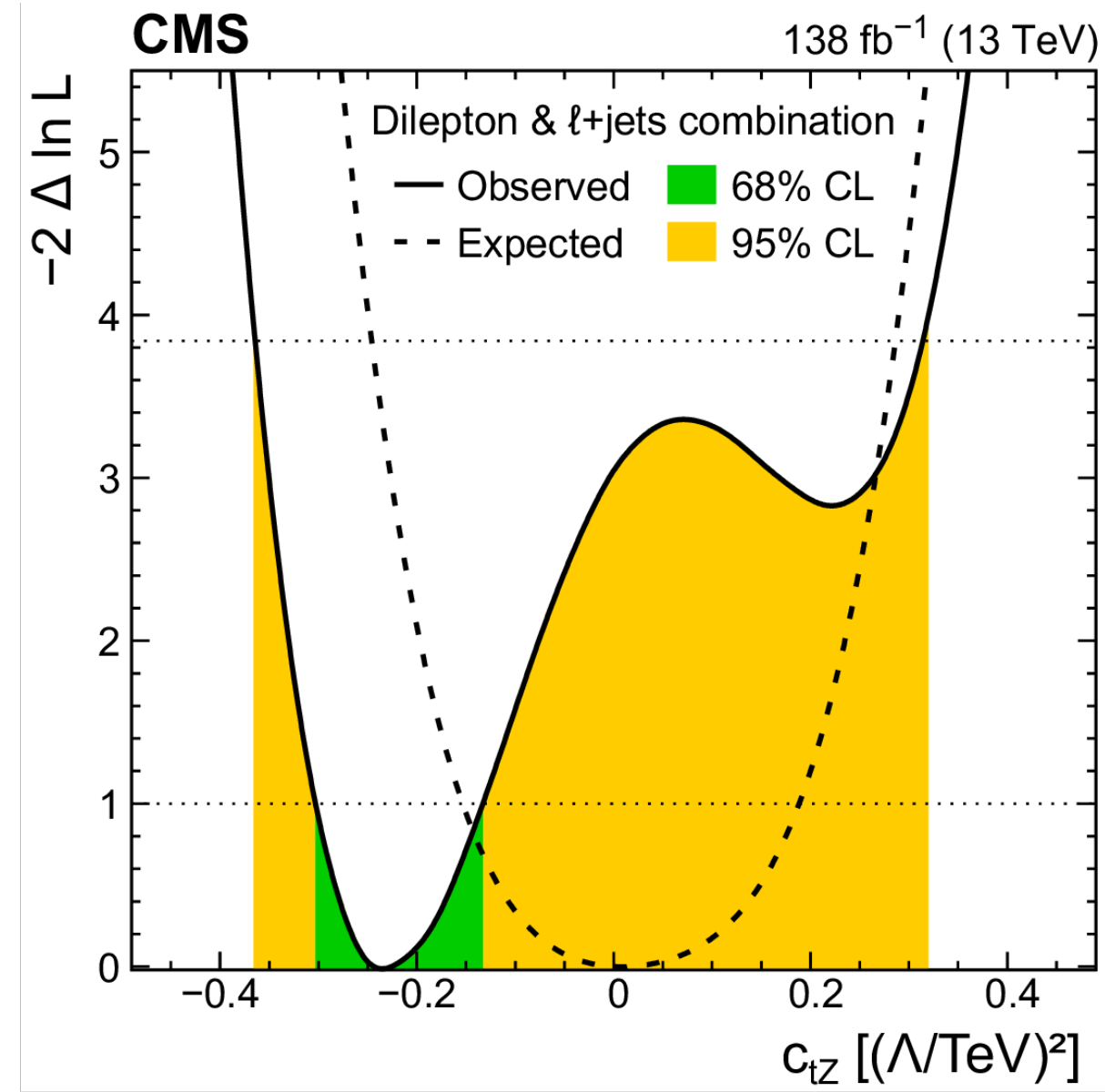
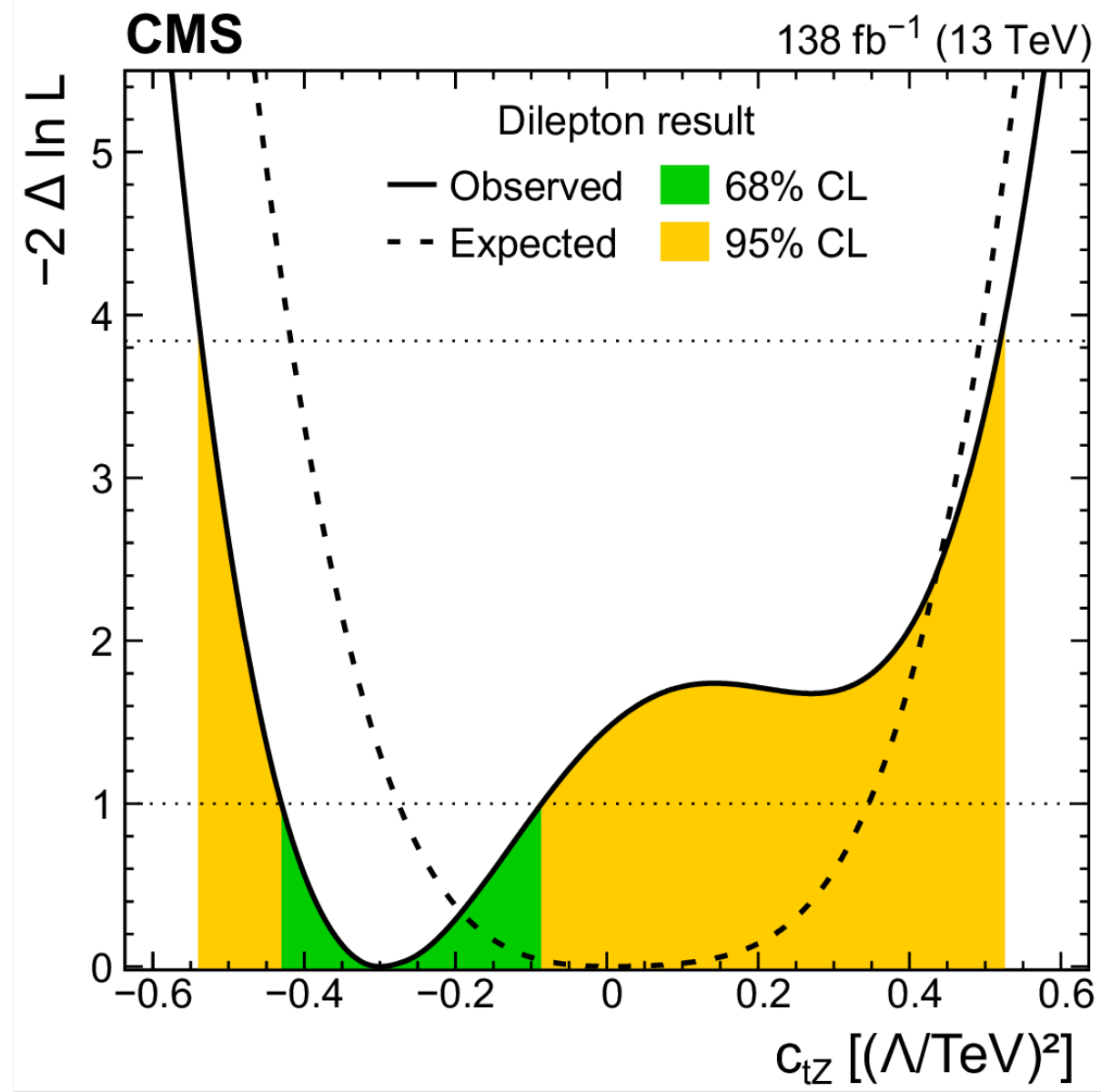
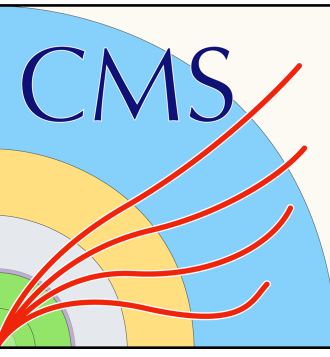


$t\bar{t}\gamma$ measurements

EFT interpretation

CMS-TOP-21-004

NEW



Wilson coefficient		Dilepton result		Dilepton & ℓ +jets combination		
		68% CL interval [$(\Lambda/\text{TeV})^2$]	95% CL interval [$(\Lambda/\text{TeV})^2$]	68% CL interval [$(\Lambda/\text{TeV})^2$]	95% CL interval [$(\Lambda/\text{TeV})^2$]	
Expected	c_{tZ}	$c_{tZ}^I = 0$	[-0.28, 0.35]	[-0.42, 0.49]	[-0.15, 0.19]	[-0.25, 0.29]
		profiled	[-0.28, 0.35]	[-0.42, 0.49]	[-0.15, 0.19]	[-0.25, 0.29]
	c_{tZ}^I	$c_{tZ} = 0$	[-0.33, 0.30]	[-0.47, 0.45]	[-0.17, 0.18]	[-0.27, 0.27]
		profiled	[-0.33, 0.30]	[-0.47, 0.45]	[-0.18, 0.18]	[-0.27, 0.27]
Observed	c_{tZ}	$c_{tZ}^I = 0$	[-0.43, -0.09]	[-0.53, 0.52]	[-0.30, -0.13]	[-0.36, 0.31]
		profiled	[-0.43, 0.17]	[-0.53, 0.51]	[-0.30, 0.00]	[-0.36, 0.31]
	c_{tZ}^I	$c_{tZ} = 0$	[-0.47, -0.03] \cup [0.07, 0.38]	[-0.58, 0.52]	[-0.32, -0.13] \cup [0.16, 0.29]	[-0.38, 0.36]
		profiled	[-0.43, 0.33]	[-0.56, 0.51]	[-0.28, 0.23]	[-0.36, 0.35]