Universidad de Oviedo
Universidá d'Uviéu
University of Oviedo

ICTEA
Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias

CMS

29-06-2022

SUSY 2022

Measurements of top quark production cross sections in CMS

Víctor Rodríguez Bouza (on behalf of the CMS Collaboration)

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

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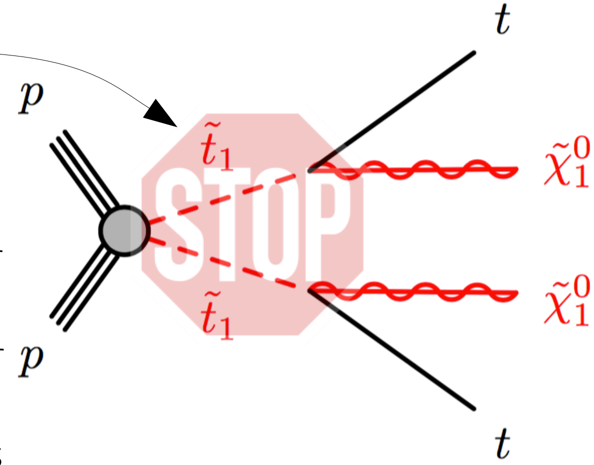
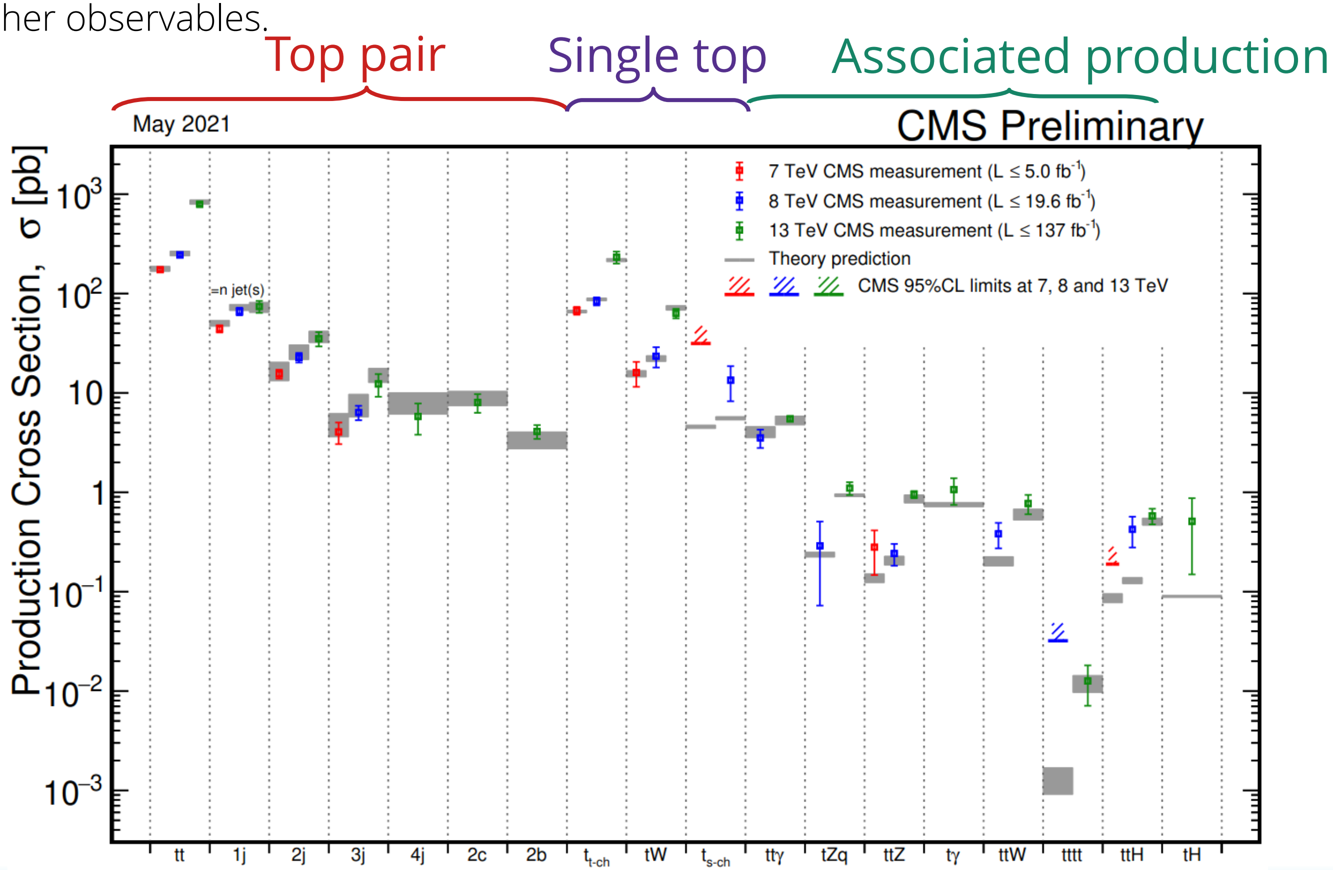
Introduction: top physics

- The top quark is the most massive particle in the SM.
  - Highest Yukawa coupling to the Higgs boson.
  - Due to its large mass, decays almost always before hadronising.
- It has large interest at LHC physics due to:
  - Multiple links with BSM proposals (e.g. SUSY extensions such as stops).
  - Large presence of its production processes (above all pair production) due to their large cross section.
- Top quark production occurs in various ways: **top pair production**, **single top** and other **associated production** processes.
  - The full Run 2 luminosity allows to make predictions with high precision of cross sections and other observables.





Results present in this talk

$\sqrt{s}$ = 7, 8 TeV

1) Inclusive ATLAS and CMS combination

arXiv:2205.13830, sub. to JHEP

$\sqrt{s}$ = 13 TeV

2) Inclusive and differential tW

CMS-PAS-TOP-21-010

3) Differential and multidifferential ttbar+jets

CMS-PAS-TOP-20-006

4) Inclusive ttW process

CMS-PAS-TOP-21-011

5) Search for central exclusive production of ttbar + protons

CMS-PAS-TOP-21-007

6) Inclusive and differential ttγ and EFT interpretation

JHEP 05 (2022) 091

Inclusive ATLAS and CMS combination at √s = 7 and 8 TeV

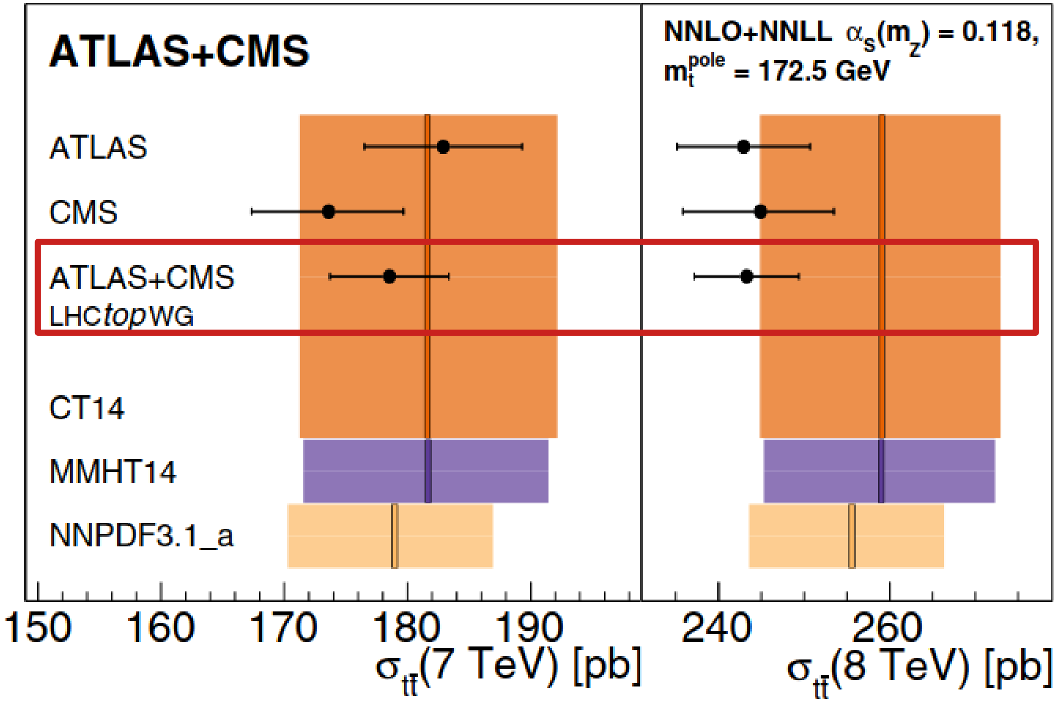
arXiv:2205.13830, sub. to JHEP

- Aim: combine the best top quark pair production cross section measurements at 7 and 8 TeV from both collaborations, and check other observables such as m_t^{pole} and $\alpha_S(m_Z)$.
- Methodology: combine **at the same time** the measurements at both energies using `Convino`, to allow taking into account the individual post-fit correlations between uncertainties from CMS' measurement.

ATLAS merged uncertainties	Value	CMS uncertainties
Lepton ID and energy resolution	HALF	Lepton ID and energy resolution
JES flavour composition/specific response	HIGH	JES flavour composition
	–LOW	b-jet fragmentation tune
	LOW	b-jet neutrino decay fraction
JES modelling	HALF	JES: AbsoluteMPFBias 7 TeV
	HALF	JES: AbsoluteMPFBias 8 TeV
JES central/forward balance	HIGH	JES: RelativeFSR 7 TeV
	HIGH	JES: RelativeFSR 8 TeV
tW background	HIGH	tW single top quark correlated
	LOW	tW single top quark 7 TeV
	LOW	tW single top quark 8 TeV
Diboson	HIGH	Diboson correlated
	LOW	Diboson 7 TeV
	LOW	Diboson 8 TeV
$t\bar{t}$ scale choice	HALF	$t\bar{t}$ scale choice
	HALF	$t\bar{t}$ scale choice (extrapolation)
$t\bar{t}$ generator	LOW	Top-quark p_T
	LOW	Top-quark p_T (extrapolation)
	–LOW	ME generator
	LOW	ME/PS matching
	LOW	ME/PS matching (extrapolation)
	–LOW	Colour reconnection
	–LOW	Underlying-event tune
Each PDF CT10 eigenvector	FULL	Each PDF CT10 eigenvector
Integrated luminosity	0.1	Integrated luminosity

Inclusive ATLAS and CMS combination at √s = 7 and 8 TeV

arXiv:2205.13830, sub. to JHEP

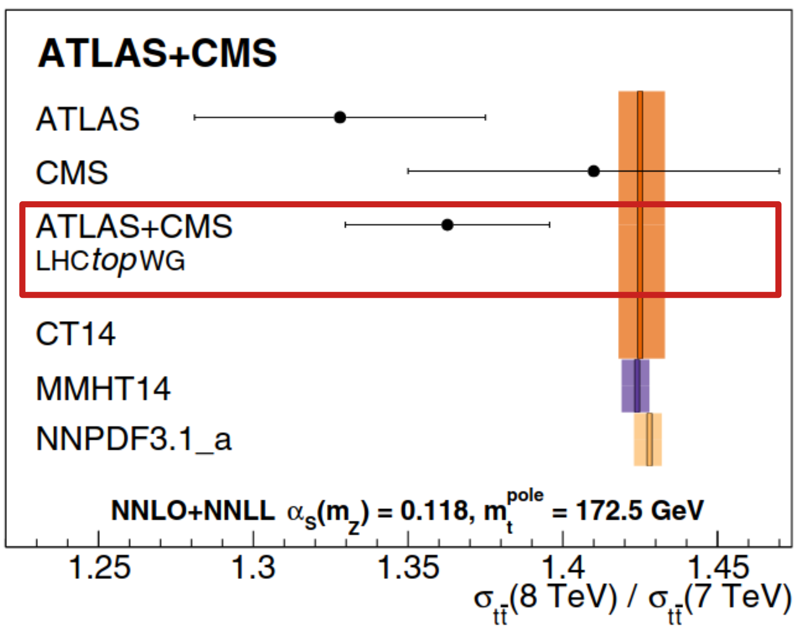


- The cross section combinations increase precision by 25% at 7 TeV and by 28% at 8 TeV from individual measurements (and by 45% in the ratio).
  - Relative uncertainties of 2.6% at 7 TeV, 2.4% at 8 TeV, and 2.3% for the ratio.

- The Pearson's correlation coefficient between the 7 & 8 TeV measurements is 0.41.

$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\ \text{TeV}\ ) \ = \ 178.5 \pm 4.7\ \text{pb}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\ \text{TeV}\ ) \ = \ 243.3^{+6.0}_{-5.9}\ \text{pb}.$$

$$R_{8/7} = 1.363 \pm 0.032.$$

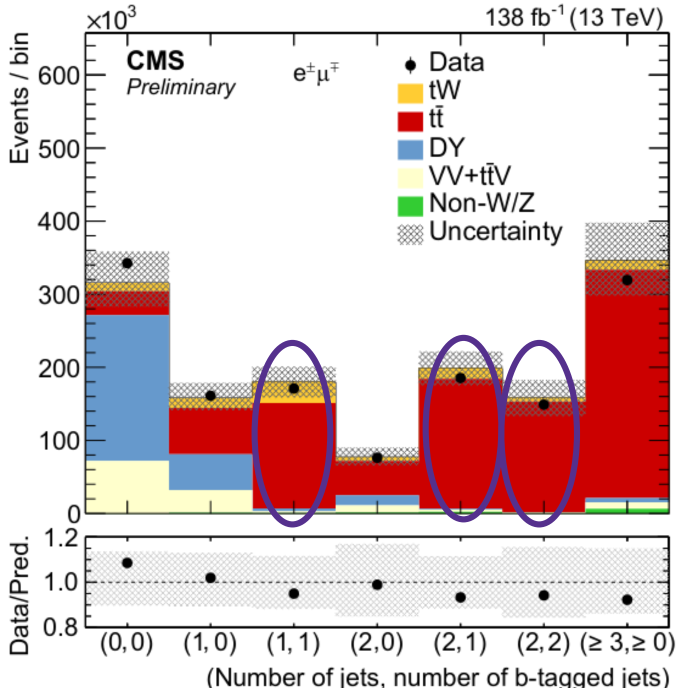


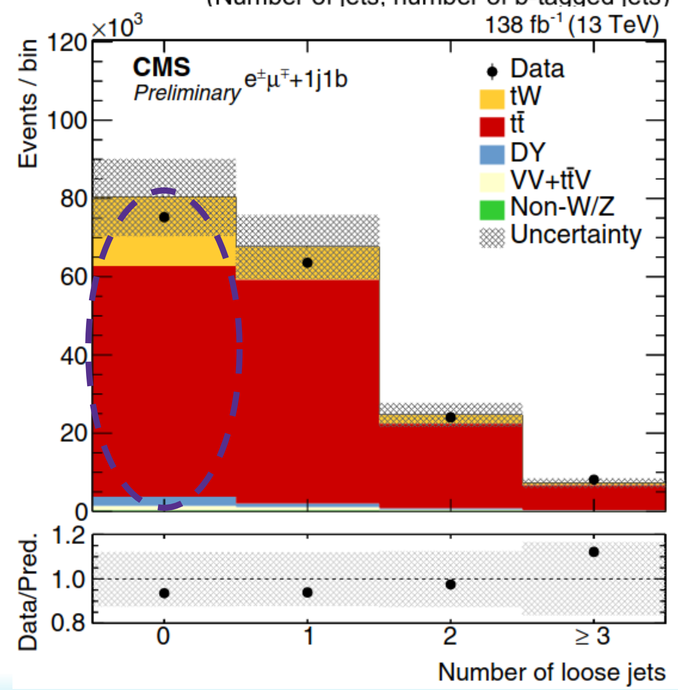
PDF set	m_t^{pole} ($\alpha_s = 0.118 \pm 0.001$)	$\alpha_s(m_Z)$ ($m_t = 172.5 \pm 1.0$ GeV)
CT14	$174.0^{+2.3}_{-2.3}$ GeV	$0.1161^{+0.0030}_{-0.0033}$
MMHT2014	$174.0^{+2.1}_{-2.3}$ GeV	$0.1160^{+0.0031}_{-0.0030}$
NNPDF3.1_a	$173.4^{+1.8}_{-2.0}$ GeV	$0.1170^{+0.0021}_{-0.0018}$

Inclusive and differential tW

CMS-PAS-TOP-21-010

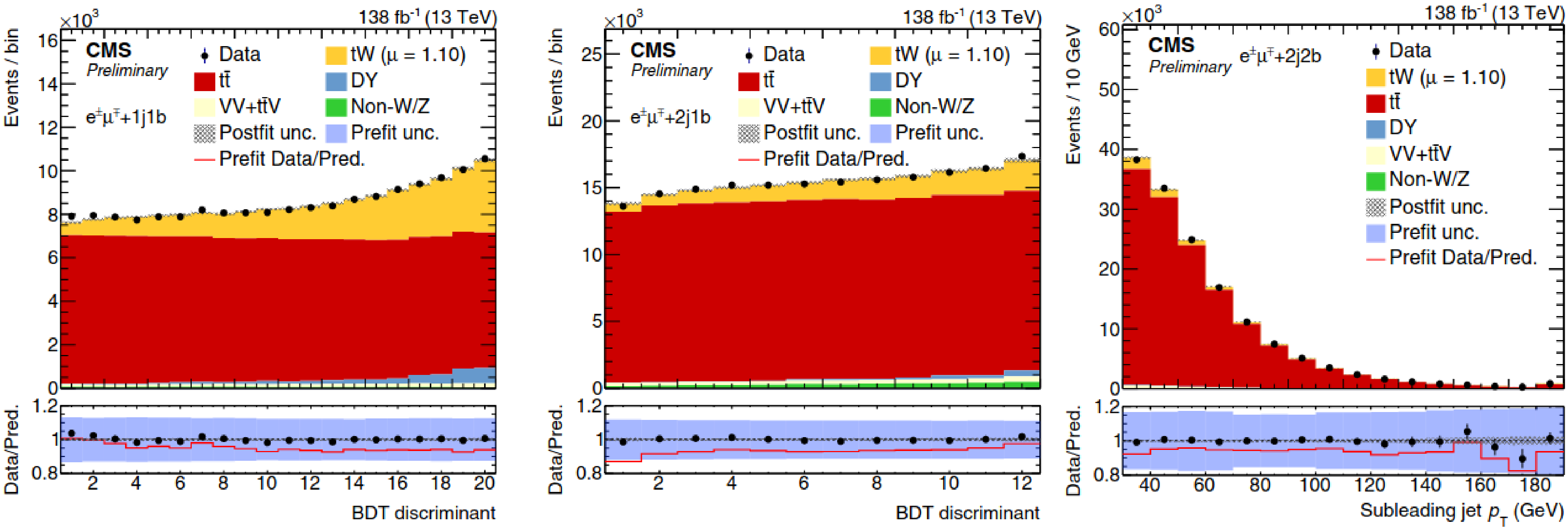
- Baseline selection: dileptonic eμ channel. Then, different signal regions are used for the differential and inclusive measurement, defined depending on the presence of jets and b-tagged jets.
- Inclusive measurement: 1j1b, 2j1b and 2j2b regions are used to perform a maximum-likelihood fit to extract the signal.
- Differential measurement: 1j1b region is chosen and enhanced by vetoing the presence of less energetic (20 GeV < p_T < 30 GeV) jets. Then, the signal extraction and unfolding to a fiducial region in particle level (defined to mimic the signal region) are done at the same time in a maximum likelihood fit. Results are normalised to the fiducial cross section.





Inclusive and differential tW

CMS-PAS-TOP-21-010



$$79.2 \pm 0.8(\text{stat})^{+7.0}_{-7.2}(\text{syst}) \pm 1.1(\text{lumi})\ \text{pb}$$

- Inclusive result shows a **~10% total uncertainty**, systematically dominated.
  - Leading sources being from experimental (e.g. JES) and also modelling (e.g. FSR) origins.
- Agrees with expectations at aNNLO and aN^{3}LO:

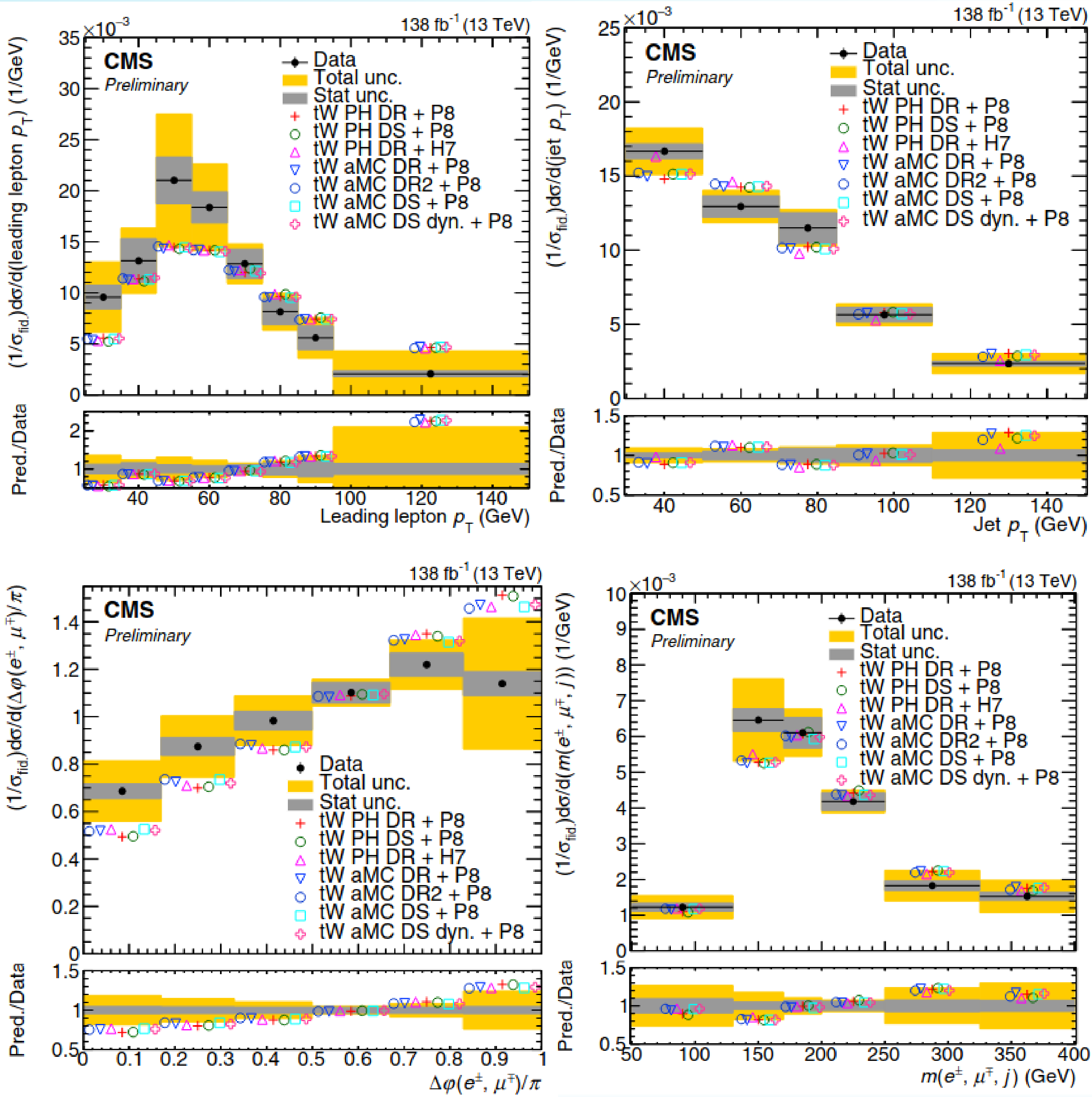
aNNLO (QCD) $\sigma_{\text{pred.}} = 71.7 \pm 1.8(\text{scale}) \pm 3.4(\text{PDF})\text{pb}$ *PoS DIS2015 (2015) 170*

aN^{3}LO (QCD) $\sigma_{\text{pred.}} = 79.5^{+1.9}_{-1.8}(\text{scale})^{+2.0}_{-1.4}(\text{PDF})\text{pb}$ *JHEP 2021, 278 (2021)*

Inclusive and differential tW

CMS-PAS-TOP-21-010

- Differential results **overall agree with expectations** from multiple models.
  - Tensions are appreciable in the leading lepton p_T and the $\Delta\varphi$ variables.

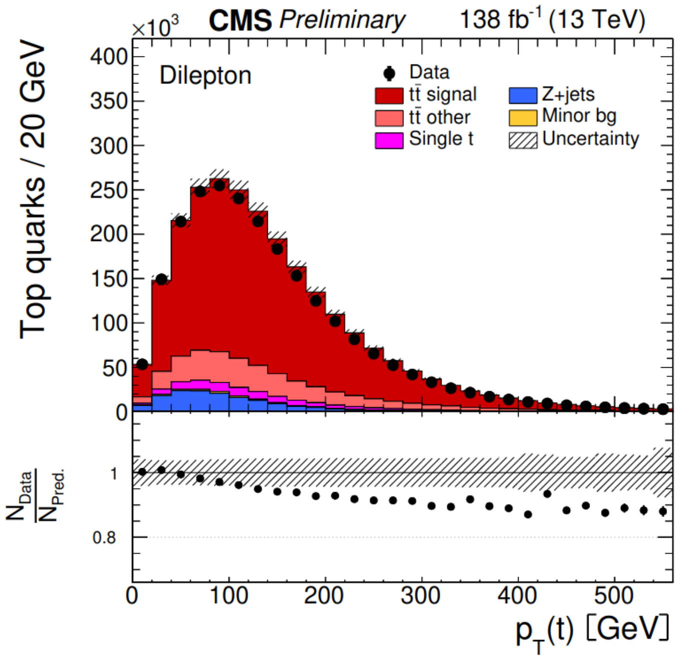


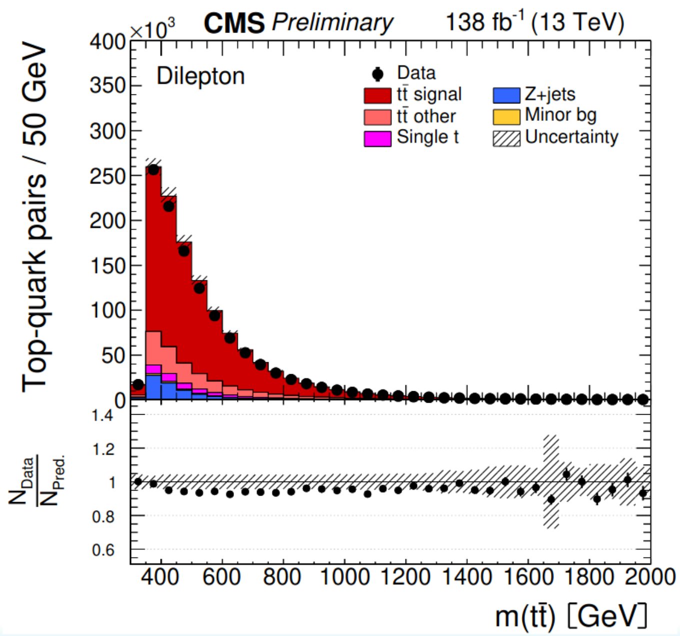
- All models show similar compatibility with data.
  - No preference can be given to any of them.
  - Points to small effect of tt/tW interference in this fiducial region & distributions.

Differential and multidifferential ttbar+jets

CMS-PAS-TOP-20-006

- Event selection: dileptonic events are chosen (eμ, μμ and ee). Events must have two isolated oppositely charged leptons and **at least two jets with at least one of them being b-tagged**. Other cuts are imposed to reduce backgrounds in the same flavour channels.
- The ttbar system is reconstructed by using the information of the two leptons, the jets and the p_T^{miss} of the system, as well as the constraints of the top and W masses.
- Signal extraction is done by background subtraction.
- Unfolding to both particle and parton levels is done using the `TUnfold` package. Multi-dimensional distributions are unfolded by parsing them as one-dimensional variables.

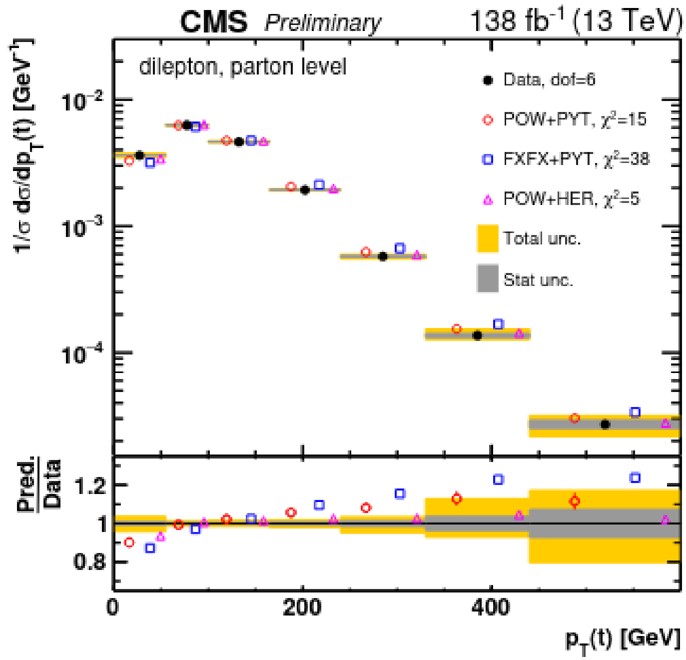


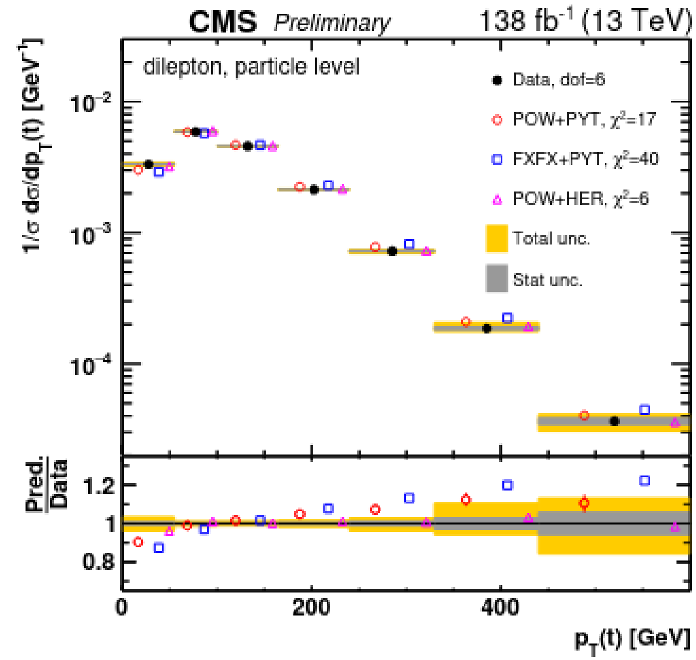


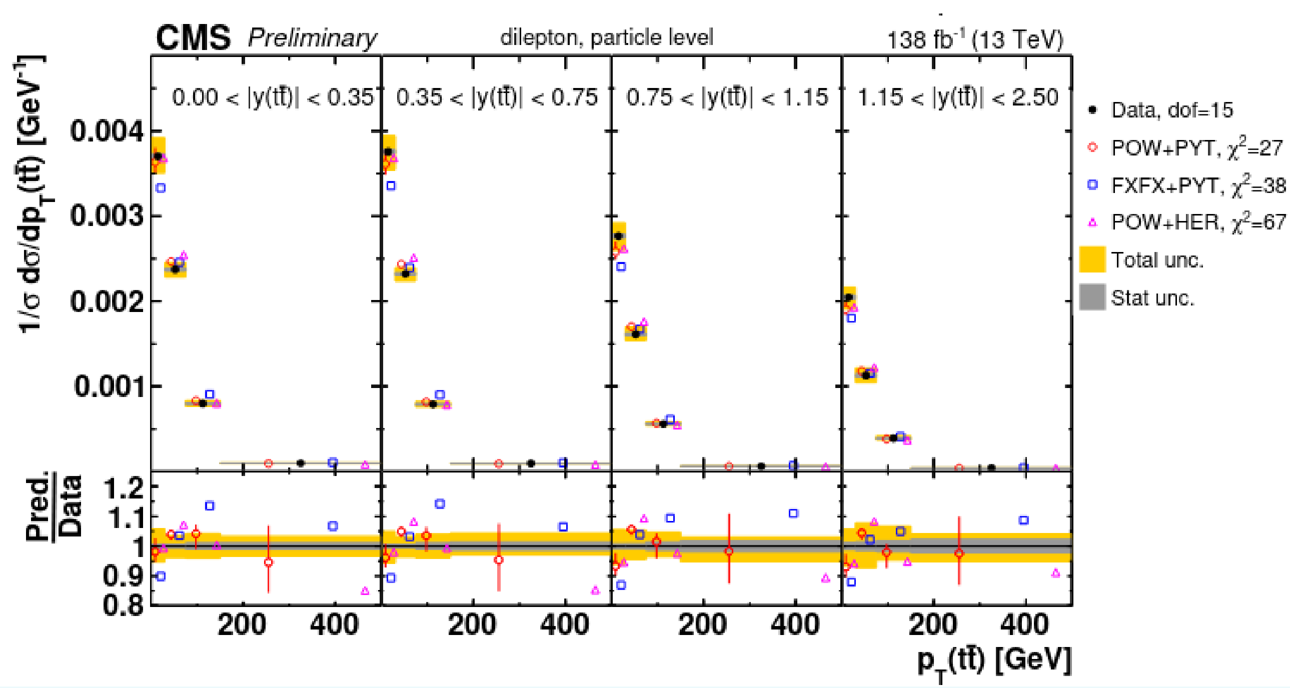
Differential and multidifferential ttbar+jets

CMS-PAS-TOP-20-006

- Multiple distributions are unfolded for **both parton and particle** level.
- Top quark observables are separated between top and anti-top quark.
- In general terms, uncertainties have been reduced from previous results (2016-only) by a factor 2.



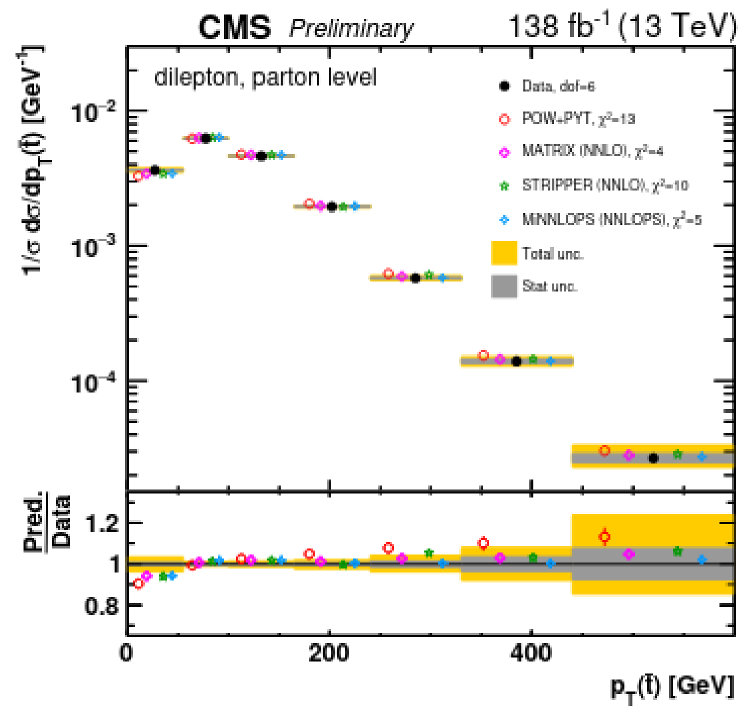




Differential and multidifferential ttbar+jets

CMS-PAS-TOP-20-006

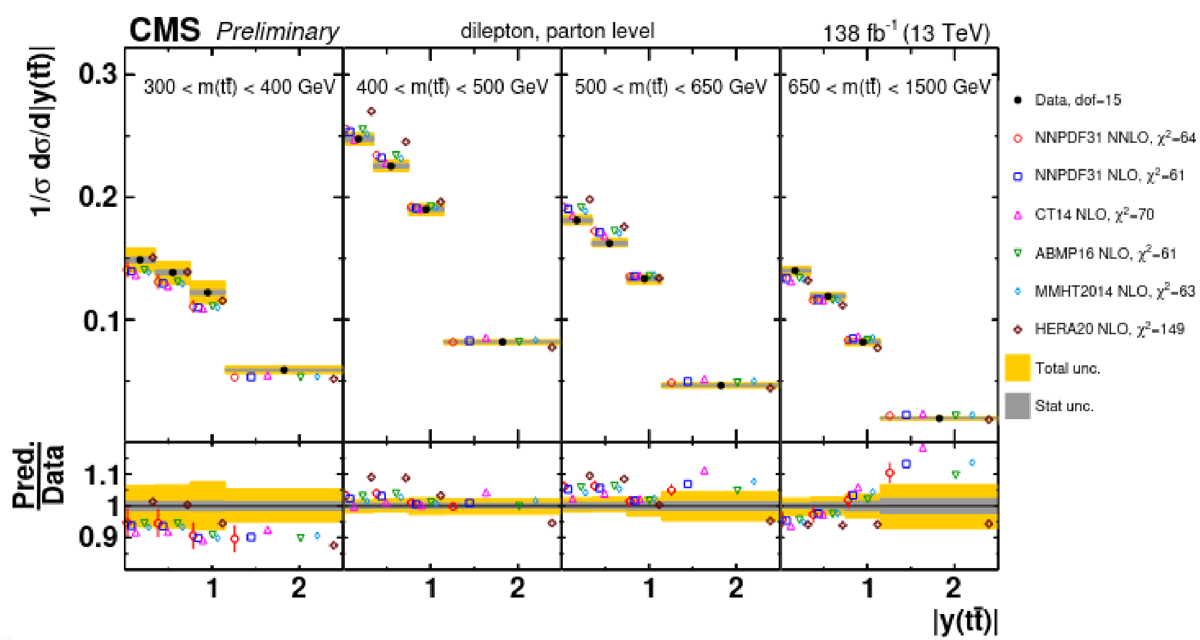
- Differential measurements depending on **different PDF sets**…
  - NNPDF3.1, CT14, ABMP16, MMHT2014, HERAPDF2.0.



- …are done, as well as **comparisons with higher-order theoretical predictions**.
  - aN^{3}LO, MATRIX (NNLO), STRIPPER (NNLO) and MiNNLOPS (NNLO+PS).

- On average, **NNLO comparisons are comparable** (though not necessarily better) **to current NLO+PS**.

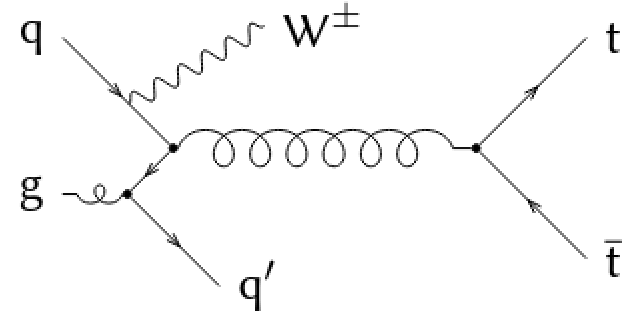
- **Data** clearly **provides discrimination power** (depending on the distribution seen) **between the different PDF** sets.

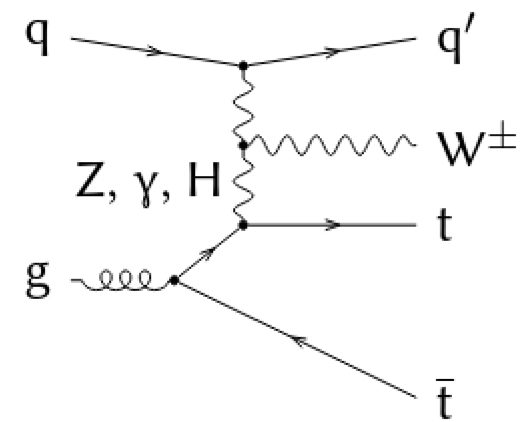


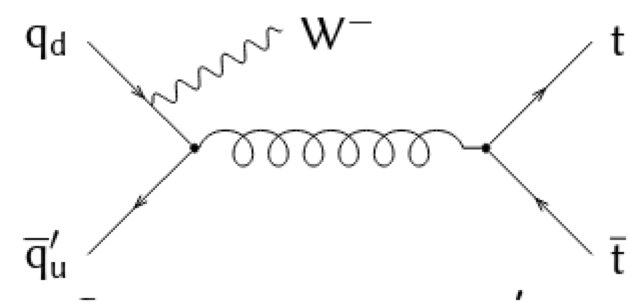
Inclusive ttW process

CMS-PAS-TOP-21-011

- Event selection: either two or three leptons.
  - **Dileptonic** events must be of same sign and should have at least two jets with at least two loosely b-tagged jets, or one strongly b-tagged one.
  - For **trileptonic** events, the sum of charges of leptons must be 1 or -1 and should have at least two jets with at least one b-tagged jet.
- Signal extraction: is done through a maximum-likelihood fit.
  - In the **dileptonic** categories, an MVA (neural network) is trained to multiclassify the signal and other three nodes: nonprompt leptons background, ttZ+ttH and ttγ. The signal's output discriminant is used for the fit.
  - For the **trileptonic**, classification depending on the number of jets, b-tagged jets, and lepton charge is done and then the invariant mass of the three-lepton system is used as discriminating variable for the signal extraction.







Inclusive ttW process

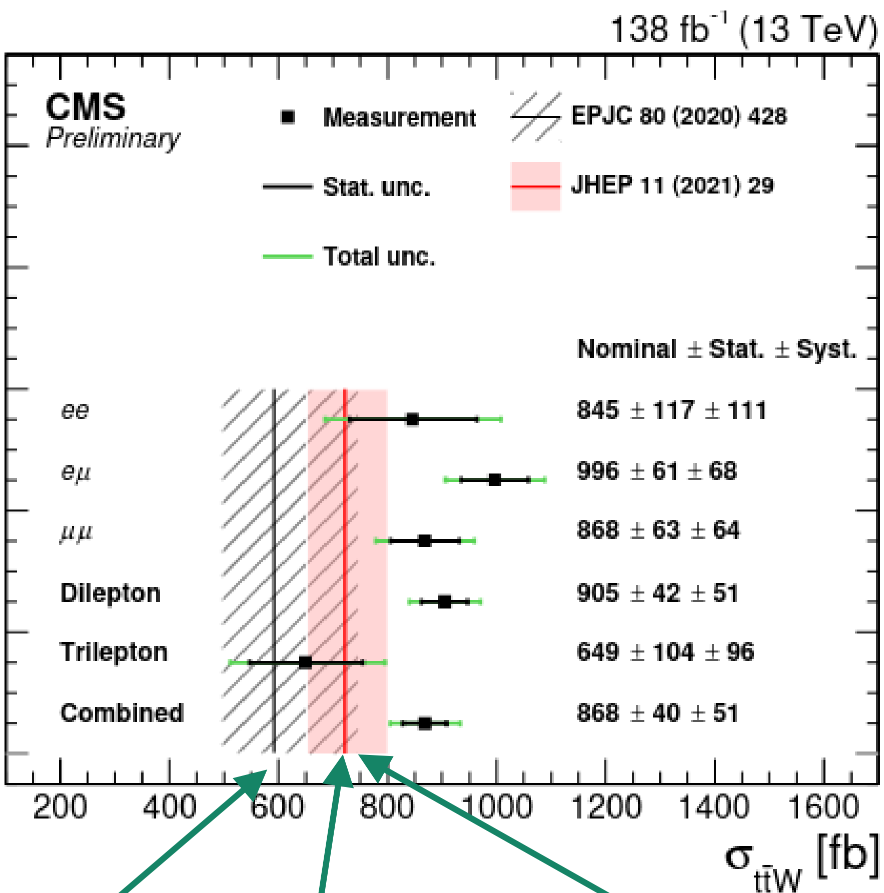
CMS-PAS-TOP-21-011

$$\sigma_{t\bar{t}W} = 868 \pm 40\,(\text{stat})^{+52}_{-50}\,(\text{syst})\text{ fb}$$

$$\sigma_{t\bar{t}W+} = 553^{+30}_{-29}\,(\text{stat})^{+31}_{-30}\,(\text{syst})\text{ fb}$$

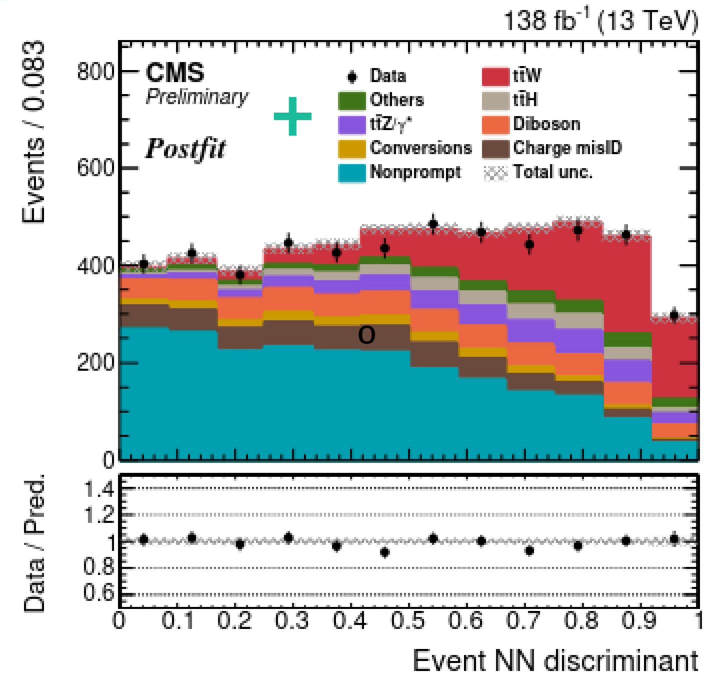
$$\sigma_{t\bar{t}W-} = 343 \pm 26\,(\text{stat}) \pm 25\,(\text{syst})\text{ fb}$$

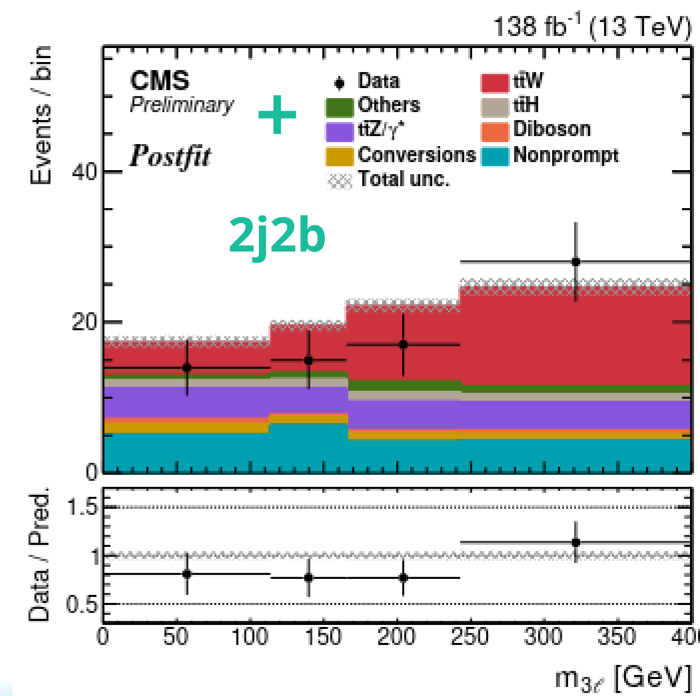
$$R_{t\bar{t}W+/t\bar{t}W-} = 1.61^{+0.15}_{-0.14}\,(\text{stat})^{+0.07}_{-0.05}\,(\text{syst})$$



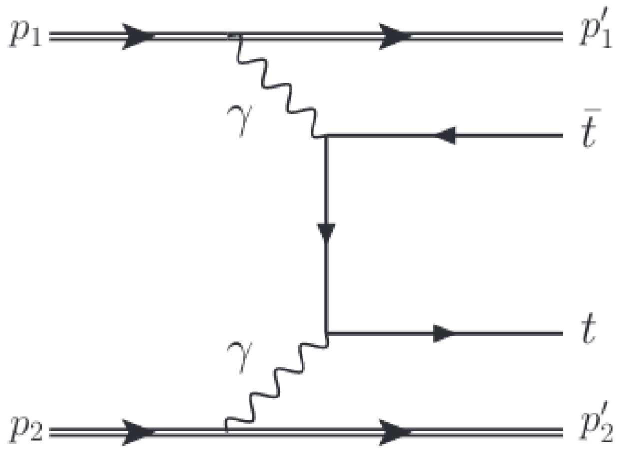
NLO (QCD) + NLO (QED)

New FxFx merging

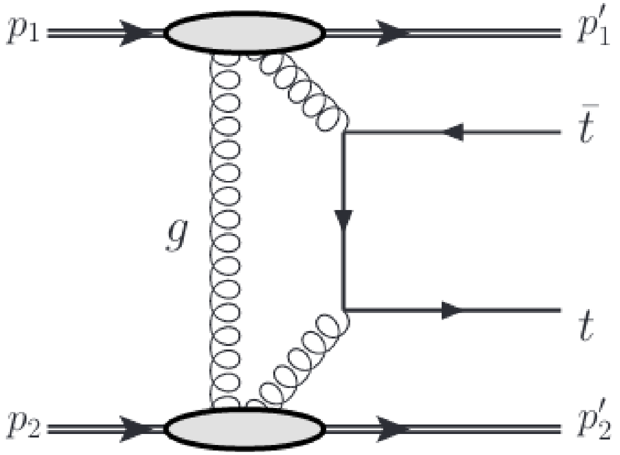




- **Central exclusive production**: both colliding protons survive the collision, though part of their energy is invested in interacting among themselves by producing a top-antitop quark pair.
- Contributions come from colour-neutral particles: either photons or pomerons.



σ ~ O(0.1 fb)

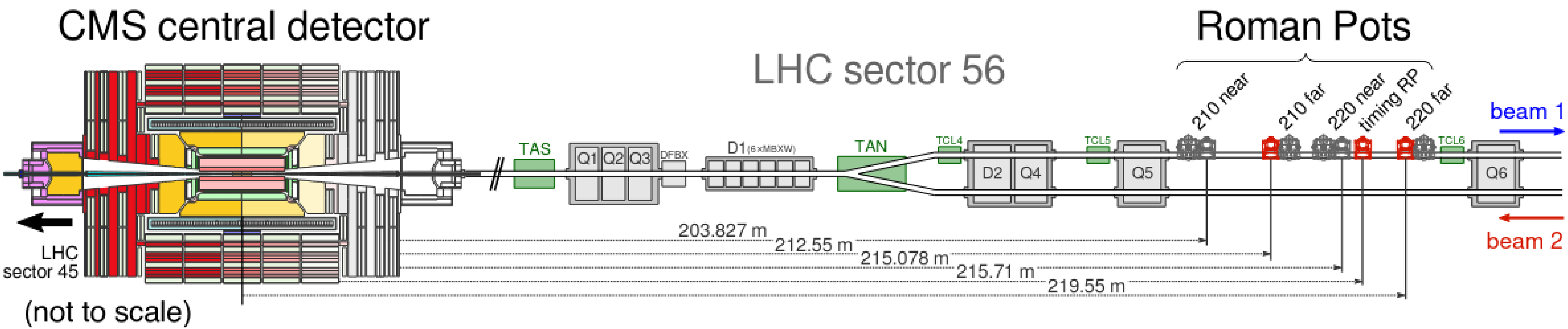


- Given the low cross section, it is only feasible to observe this process in the HL-LHC. However, BSM contributions might enlarge this cross section, making it noticeable with current data.

Search for central exclusive production of ttbar + protons

CMS-PAS-TOP-21-007

- Information is used from both CMS and TOTEM.
- **TOTEM**: array of movable near-beam devices (roman pots or RP) that contain tracking or timing detectors installed along the LHC beam line at ~210 m from CMS interaction point.



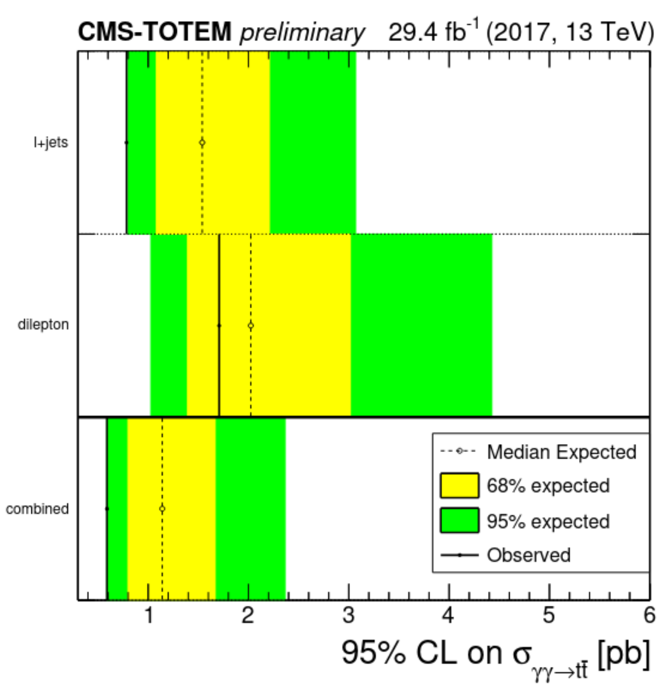
- Only data-taking runs from 2017 where all detectors from TOTEM were operational are used (thus, the **29.4 fb^{-1}**).
- The **semileptonic and dileptonic** decay modes of ttbar are selected for this analysis, yielding two main categories for the event selection.
  - In both, **the presence of one proton track reconstructed in proton in each arm** is required.
  - For the semileptonic category, events must have one electron/muon and at least two b-tagged jets and at least two jets that fail the b-tag selection.
  - For the dileptonic category, events must have at least two b-tagged jets.
- Two MVA are constructed to enhance the discrimination between the signal and the backgrounds (being the main the top quark pair production). Maximum likelihood fits are done to extract upper limits for the cross sections.

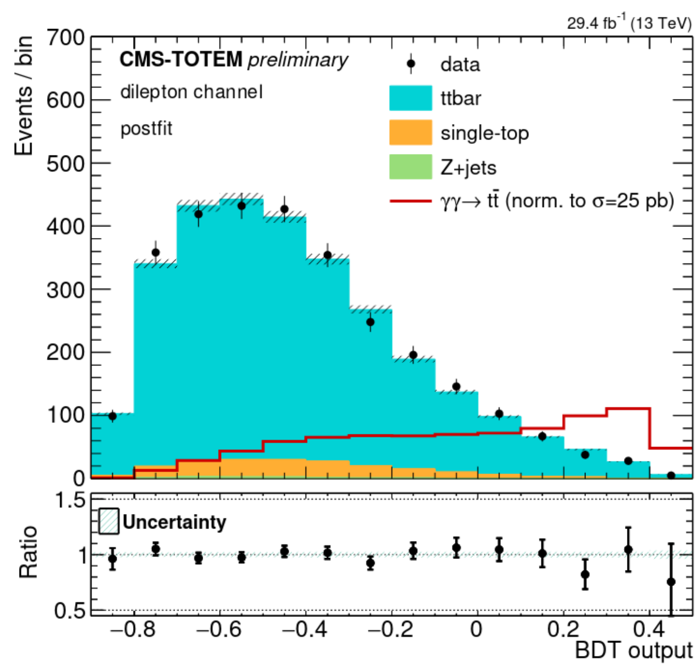
Search for central exclusive production of ttbar + protons

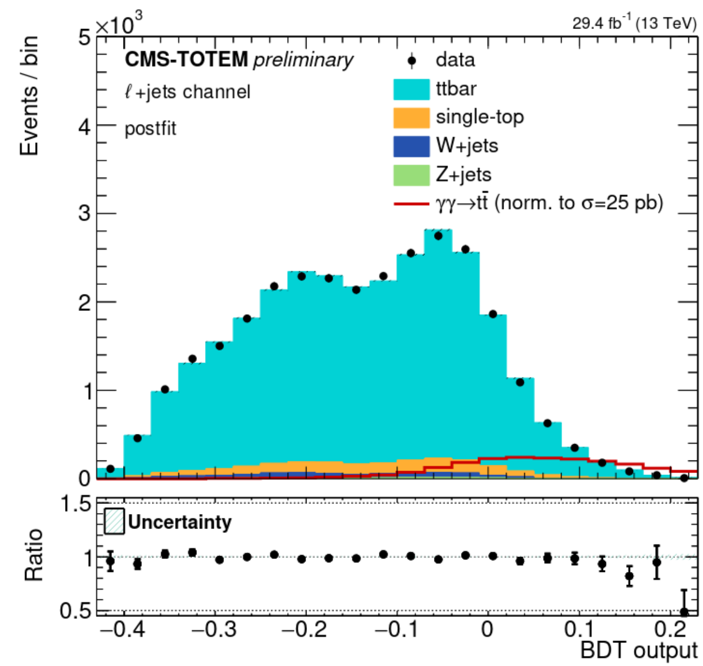
CMS-PAS-TOP-21-007

- This result (the first time this process is searched using tagged intact protons) allows to a (observed) combined upper limit of 0.59 pb (95% CL).

- The result depends mostly on statistics, being systematic uncertainties on the limit ~10%.
  - Leading sources are background normalisation, FSR modelling, JECs, and proton reconstruction.

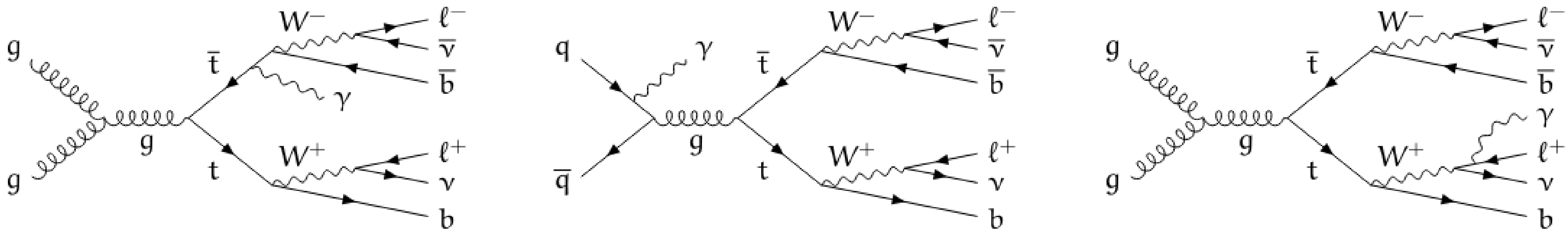






Inclusive and differential $t\bar{t}\gamma$ and EFT interpretation

JHEP 05 (2022) 091



- Event selection: two opposite charged leptons, exactly one photon and at least one b-tagged jet. Other cuts (such as removing the Z peak window) are imposed to reduce the background contamination.

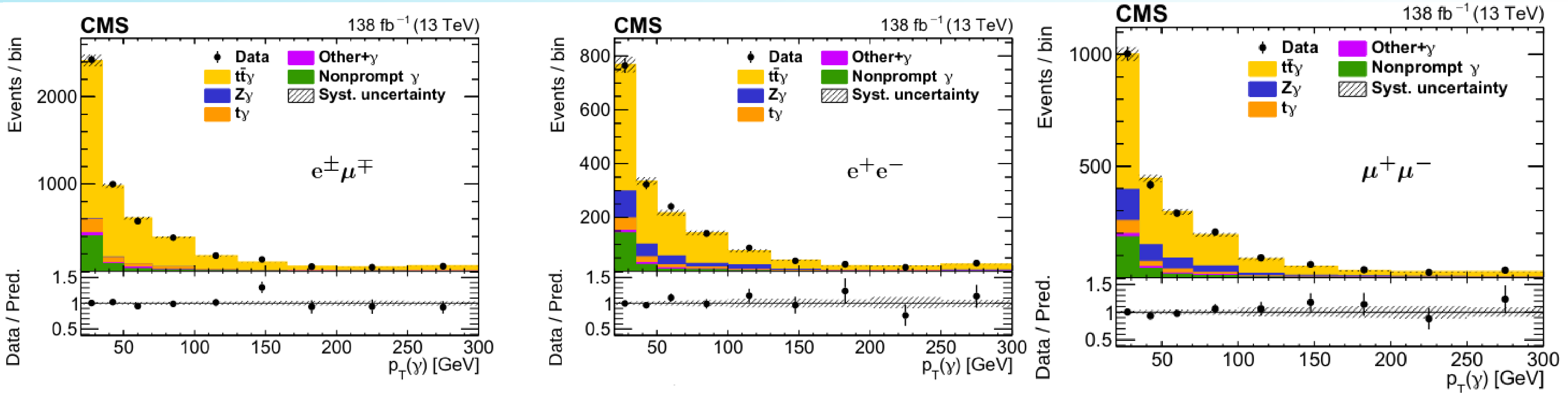
- Inclusive measurement: profiled maximum-likelihood fit is done over the reconstructed photon p_T to extract the signal and perform the measurement

- Differential measurement: signal extraction is done by subtracting the estimated backgrounds to data and performing the unfolding with **`TUnfold`**, without any need for regularisation. Results are normalised to fiducial cross section.

- Effective field theory interpretation: new-physics hypothesis are parametrised in terms of the Wilson coefficients c_{tZ} and c^{I}_{tZ}, after assuming for the tWb vertex c_{uW}=0. The effect of these modifications are probed in the photon p_T distribution at detector level. The results are also combined with other CMS measurements of $t\bar{t}\gamma$ in the semileptonic decay channel.

Inclusive and differential $t\bar{t}\gamma$ and EFT interpretation

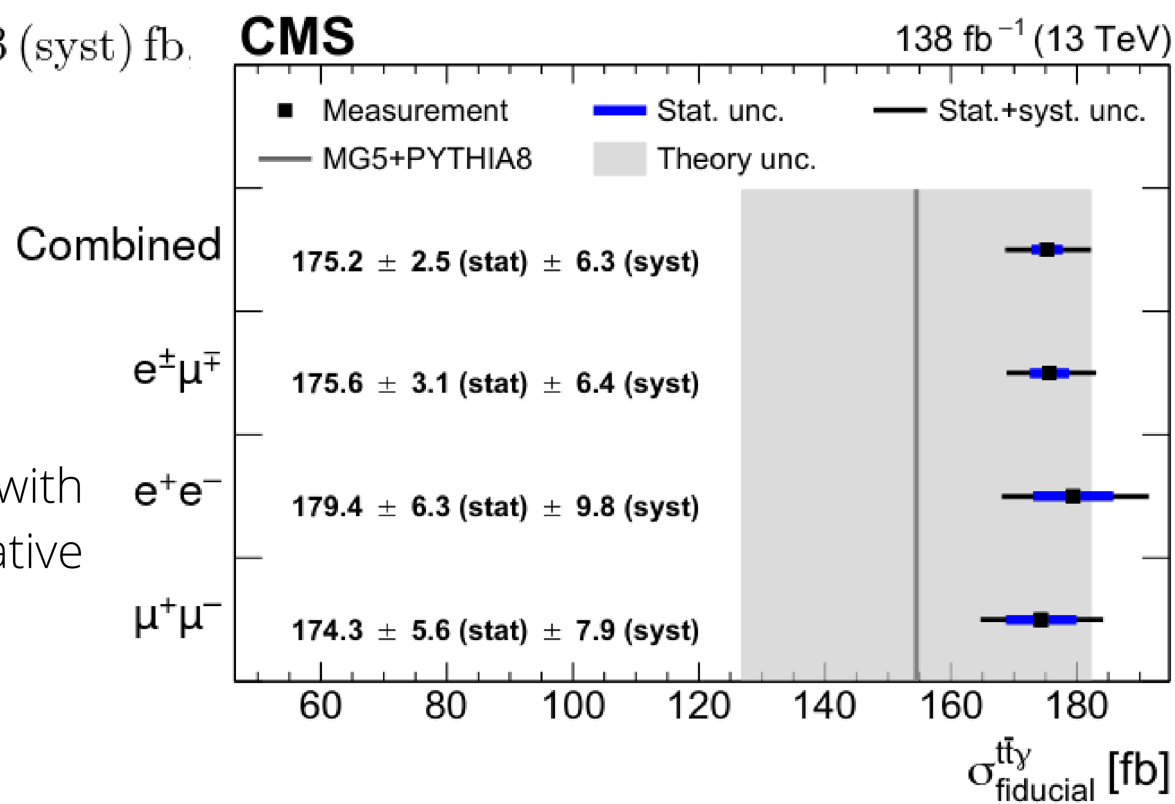
JHEP 05 (2022) 091



$$\sigma_{\text{fid}}(\text{pp} \rightarrow t\bar{t}\gamma) = 175.2 \pm 2.5\,(\text{stat}) \pm 6.3\,(\text{syst})\ \text{fb}$$

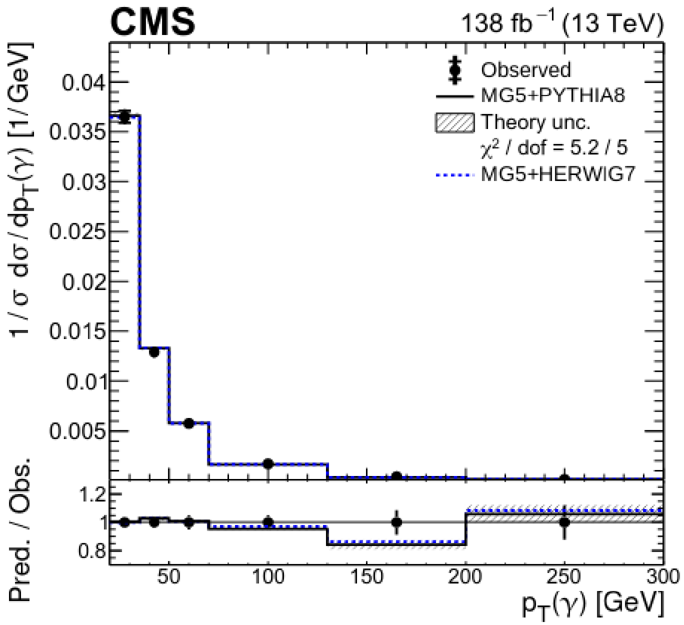
$$\sigma_{\text{SM}}(\text{pp} \rightarrow t\bar{t}\gamma) = 155 \pm 27\ \text{fb}.$$

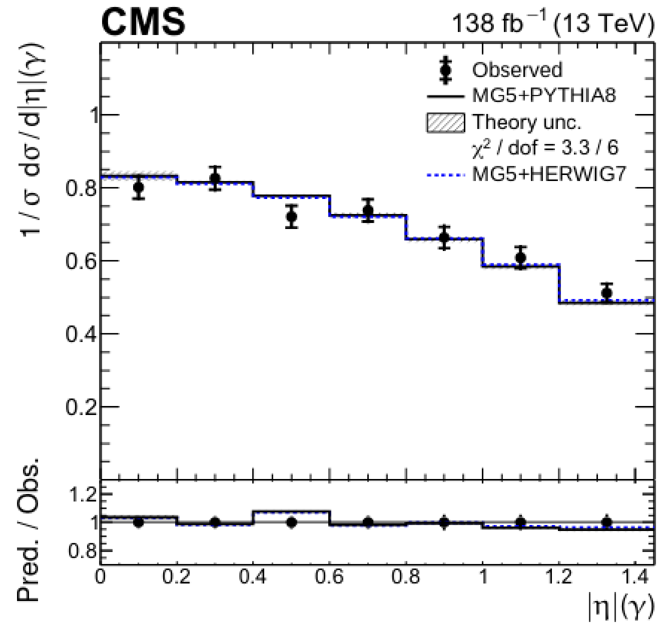
- The inclusive result is in agreement with the SM prediction, with a total 4% relative uncertainty

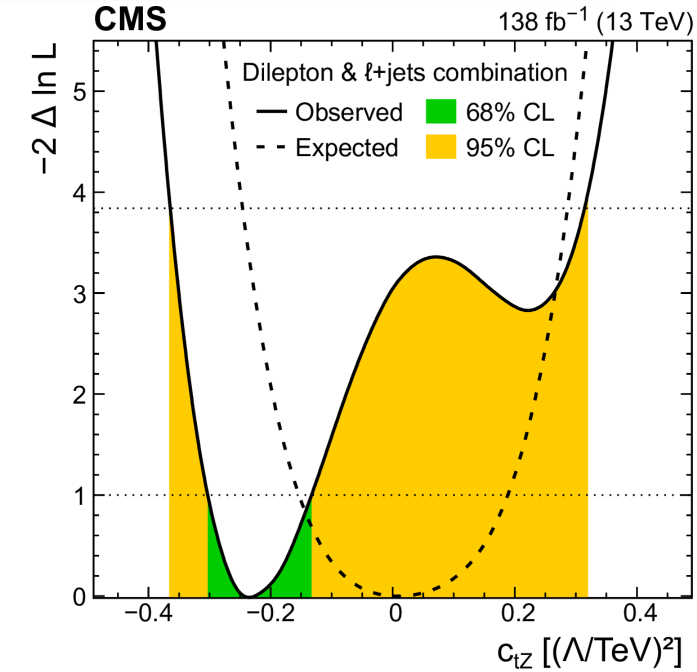


Inclusive and differential ttγ and EFT interpretation

JHEP 05 (2022) 091

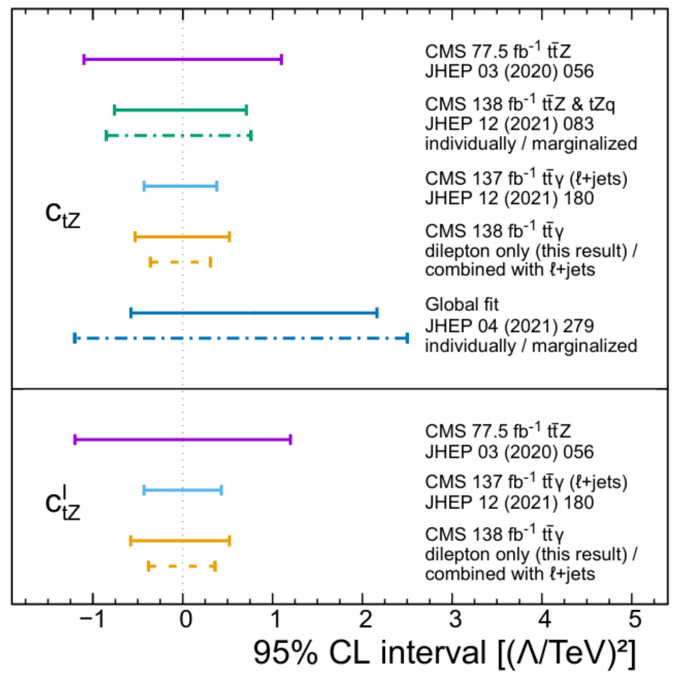


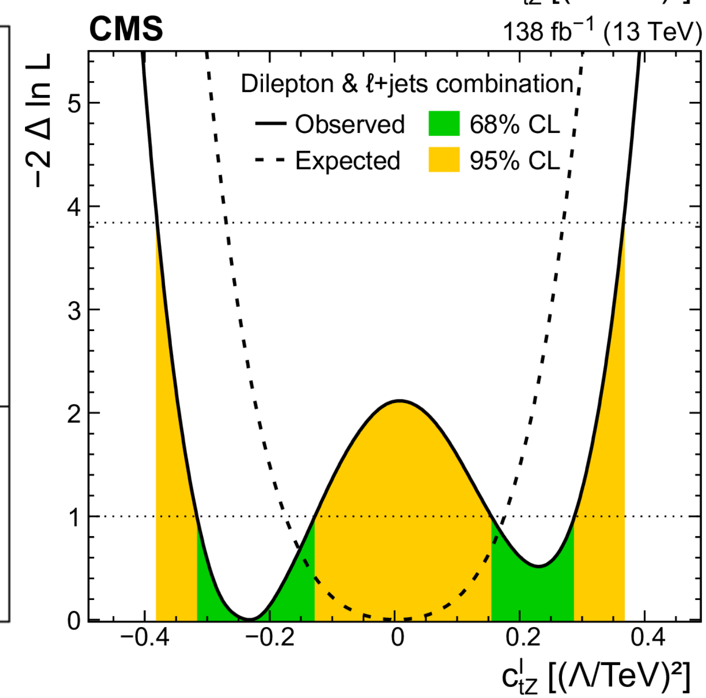




- The differential results **do not deviate significantly from SM** expectations.

- The interpretation in the framework of SMEFT yield the current best experimental limits on these two Wilson coefficients.





Summary

- The latest CMS measurements from top processes have been made in multiple production modes.
  - The **combination of top quark pair productions** at $\sqrt{s}$ = 7 and 8 TeV with ATLAS yield the most precise measurements of inclusive cross sections at those energies.
  - Inclusive (with ~10% total unc.) and differential measurements (10-50%) have been done in the eμ **tW** dileptonic channel, in overall agreement with SM expectations.
  - Extensive **(multi)differential** measurements of the **top-antitop pair production** have been done with the full Run 2 dataset, with comparisons with multiple PDF sets and NNLO generators.
  - The **ttW process** has been measured inclusively with the full Run 2, with small tensions with respect to the SM predictions (agreement within two sigmas).
  - For the first time, CMS has made a search for the **top-antitop pair production** in its **central production** mode, imposing upper limits statistically dominated.
  - Finally, the **ttγ process** has been measured inclusively and differentially showing overall agreement with SM and an interpretation in terms of SMEFT has been done depending on the two c_{tZ} and c^{I}_{tZ} Wilson coefficients, imposing the (current) best limits upon them.

Thanks for your attention

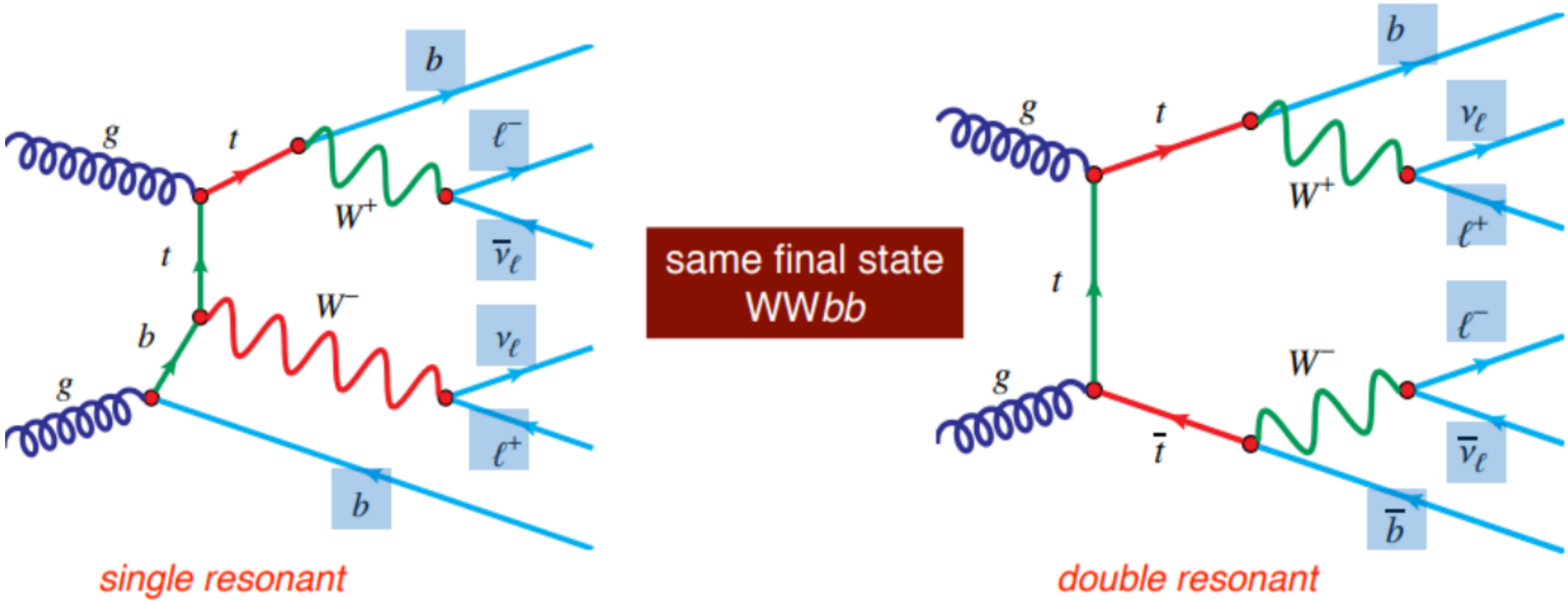
SUSY 2022

Backup slides

Inclusive ATLAS and CMS combination at √s = 7 and 8 TeV

arXiv:2205.13830, sub. to JHEP

Uncertainty	$\Delta\sigma_{t\bar{t}}$(7 TeV) [%]	$\Delta\sigma_{t\bar{t}}$(8 TeV) [%]
Trigger	0.6	0.5
Lepton (mis-)ID, isolation and energy	1.0	0.9
JES flavour composition	0.4	0.4
JES modelling	< 0.1	0.1
JES central/forward balance	0.2	0.2
b-jet (mis-)ID	0.4	0.4
Pile-up	0.2	0.2
tW background	0.8	0.6
Drell–Yan background	0.7	0.4
Diboson background	0.2	0.4
$t\bar{t}$ generator	0.8	0.8
$t\bar{t}$ scale choice	0.4	0.4
PDF	0.4	0.3
Integrated luminosity	1.7	1.7
Statistical	1.0	0.4
Total uncertainty	$^{+2.7}_{-2.6}$	$^{+2.5}_{-2.4}$



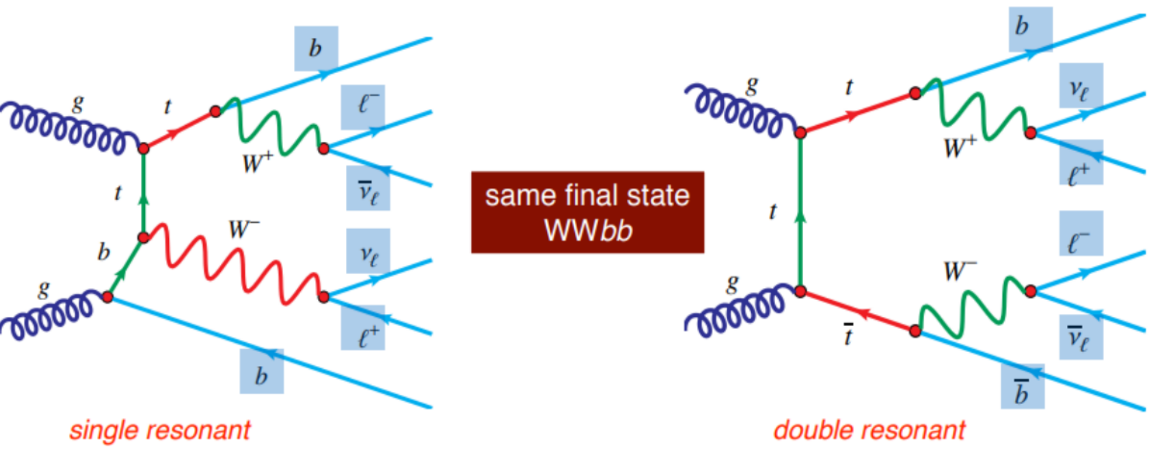
- At NLO in QCD, the tW process shows identical final states (WWbb) with the top pair quark production. This implies that, if NLO (in QCD) samples of ttbar and tW are used simultaneously in an analysis...

  1) ...double counting of events might happen.

  2) ...interference terms that appear between some of the diagrams in the calculation are not being considered.

The tW & ttbar relationship: DR method

CMS-PAS-TOP-21-010



$$|\mathcal{A}_{tWb}|^2 = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2$$
$$= |\mathcal{A}_{1t}|^2 + 2\mathrm{Re}(\mathcal{A}_{1t}\mathcal{A}_{2t}^*) + |\mathcal{A}_{2t}|^2$$

The potential issues of using together ttbar and tW MC samples can be avoided. The approaches to do so modify the tW sample as follows.

- **Diagram removal** scheme (**DR**): all Feynman diagrams that present two tops that can be on-shell ("double resonant") are removed from the calculation of tW at NLO (QCD). The resulting calculation is not gauge-invariant. Both ATLAS and CMS use this approach as nominal.

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DR1}} = |\mathcal{A}_{1t}|^2$$

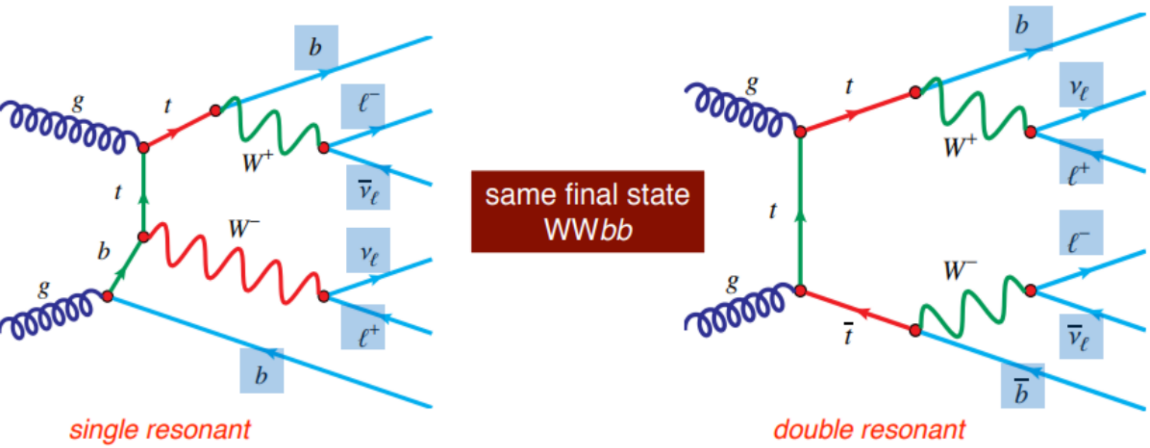
  - A small deviation from this scheme is to add to the ME calculation the interference terms that are neglected in the usual calculation. This approach is usually called **DR2** (and the common DR is then renamed to DR1). Only present in **`aMC@NLO`**.

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DR2}} = |\mathcal{A}_{1t}|^2 + 2\mathrm{Re}(\mathcal{A}_{1t}\mathcal{A}_{2t}^*)$$

Inclusive and differential tW

The tW & ttbar relationship: DS method

CMS-PAS-TOP-21-010



$$|\mathcal{A}_{tWb}|^2 = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2$$
$$= |\mathcal{A}_{1t}|^2 + 2\mathrm{Re}(\mathcal{A}_{1t}\mathcal{A}_{2t}^*) + |\mathcal{A}_{2t}|^2$$

The potential issues of using together ttbar and tW samples can be avoided. The approaches to do so modify the tW sample as follows.

- **Diagram subtraction** scheme (**DS**): to keep gauge invariance, no diagrams are removed from the calculations. Instead, an artificial term is added to the cross section calculus that goes to zero in the top mass resonance. Such a term can be constructed as:

$$|\mathcal{A}_{tWb}|^2_{\mathrm{DS}} = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2 - \mathcal{C}_{2t} \qquad \mathcal{C}_{2t}(\{p_i\}) = f(p_{Wb}^2)\,|\mathcal{A}_{2t}(\{q_i\})|^2$$

  - Where $p_{Wb} = (p_W + p_b)^2$, $\{p_i\}$ are the momenta of the external particles and the $\{q_i\}$ are the external momenta reshuffled so that the internal anti-top quark is on its mass-shell (required for gauge invariance in the $\Gamma_t \to 0$ limit).
  - The function $f(p^2_{Wb})$ can be chosen freely. Two choices are present in both `POWHEG` and `MadGraph5_aMC@NLO`:
    - **DS1**: ratio of two Breit-Wigner for the top quark before and after the reshuffling (i.e. on-shell). Used in both generators.

$$f_1(s) = \frac{(m_t\Gamma_t)^2}{(s - m_t^2)^2 + (m_t\Gamma_t)^2}$$

    - **DS2**: identic to the previous one, but modifying $m_t\Gamma_t$ by $\sqrt{s}\Gamma_t$. This makes the correction process-dependent. Only present in aMC@NLO.
  - In addition, there are different ways of doing the reshuffling of the four-momenta in `POWHEG/aMC@NLO`:
    - Using **all external particles**: default one, used in both generators.
    - Using only **initial-state particles**: only present in aMC@NLO.

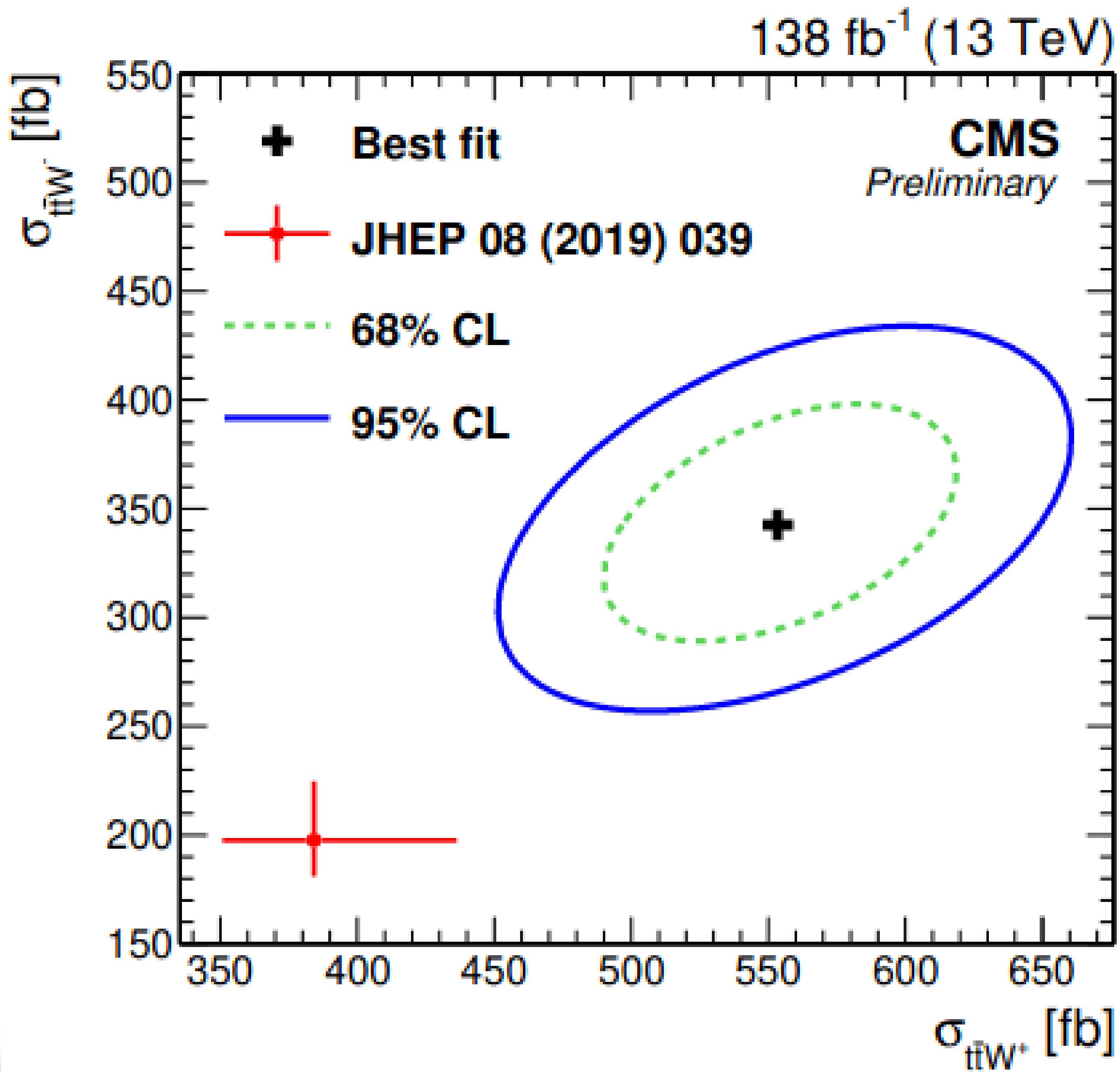
Uncertainty	$\Delta\sigma_{t\bar{t}}$(7 TeV) [%]	$\Delta\sigma_{t\bar{t}}$(8 TeV) [%]
Trigger	0.6	0.5
Lepton (mis-)ID, isolation and energy	1.0	0.9
JES flavour composition	0.4	0.4
JES modelling	< 0.1	0.1
JES central/forward balance	0.2	0.2
b-jet (mis-)ID	0.4	0.4
Pile-up	0.2	0.2
tW background	0.8	0.6
Drell–Yan background	0.7	0.4
Diboson background	0.2	0.4
$t\bar{t}$ generator	0.8	0.8
$t\bar{t}$ scale choice	0.4	0.4
PDF	0.4	0.3
Integrated luminosity	1.7	1.7
Statistical	1.0	0.4
Total uncertainty	$^{+2.7}_{-2.6}$	$^{+2.5}_{-2.4}$

Inclusive ttW process

Uncertainty breakdown and 2D comparison with predictions for ttW⁺/ttW⁻

CMS-PAS-TOP-21-011

Uncertainty type	Relative value (%)
Experimental	
Integrated luminosity	1.9
Charge misidentification	1.6
b jet 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



Inclusive and differential ttγ and EFT interpretation

Uncertainty breakdown and 2D comparison of both probed Wilson coeffs. with SM predictions

JHEP 05 (2022) 091

	Source	Correlation	Uncertainty [%] Prefit range	Postfit
Experimental	Integrated luminosity	~	1.3–3.2	1.7
	Pileup	✓	0.1–1.4	0.7
	Trigger efficiency	×	0.6–1.7	0.6
	Electron selection efficiency	~	1.0–1.3	1.0
	Muon selection efficiency	~	0.3–0.5	0.5
	Photon selection efficiency	~	0.4–3.6	1.1
	Electron & photon energy	✓	0.0–1.1	0.1
	Jet energy scale	~	0.1–1.3	0.5
	Jet energy resolution	✓	0.0–0.6	<0.1
	b tagging efficiency	~	0.9–1.4	1.1
	L1 prefiring	✓	0.0–0.8	0.3
Theoretical	Values of μ_F and μ_R	✓	0.3–3.5	1.3
	PDF choice	✓	0.3–4.5	0.3
	PS modelling: ISR & FSR scale	✓	0.3–3.5	1.3
	PS modelling: colour reconnection	✓	0.0–8.4	0.2
	PS modelling: b fragmentation	✓	0.0–2.2	0.7
	Underlying-event tune	✓	0.5	0.5
Background	Zγ correction & normalization	✓	0.0–0.2	0.1
	tγ normalization	✓	0.0–0.9	0.8
	Other+γ normalization	✓	0.3–1.0	0.8
	Nonprompt γ normalization	✓	0.0–1.8	0.7
	Size of background samples	×	1.5–7.6	0.9
	Total systematic uncertainty			3.6
	Statistical uncertainty			1.4
	Total uncertainty			3.9