12th International Workshop on the CKM Unitarity Triangle (CKM 2023)

Universidad de Oviedo

tt+X measurements by CMS and ATLAS

Barbara Alvarez Gonzalez on behalf of CMS and ATLAS collaborations

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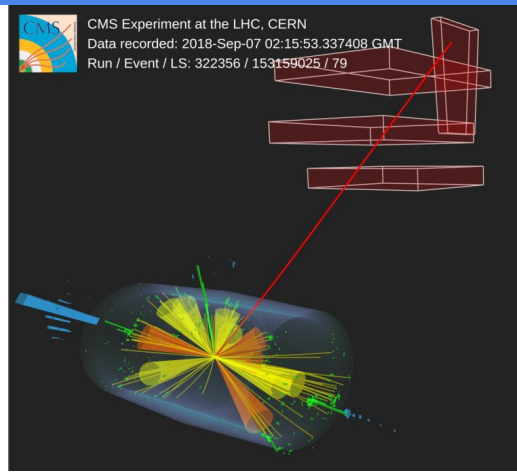
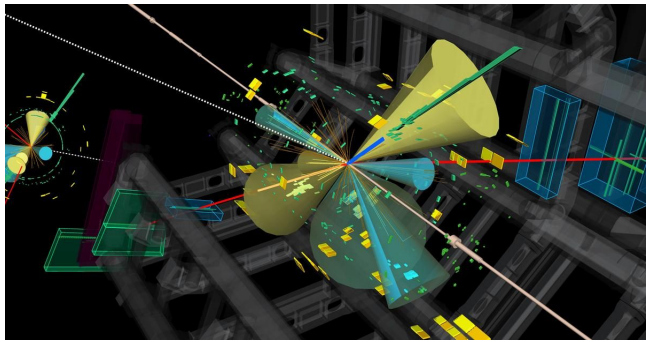
EUROPEAN UNION

European Regional Development Fund

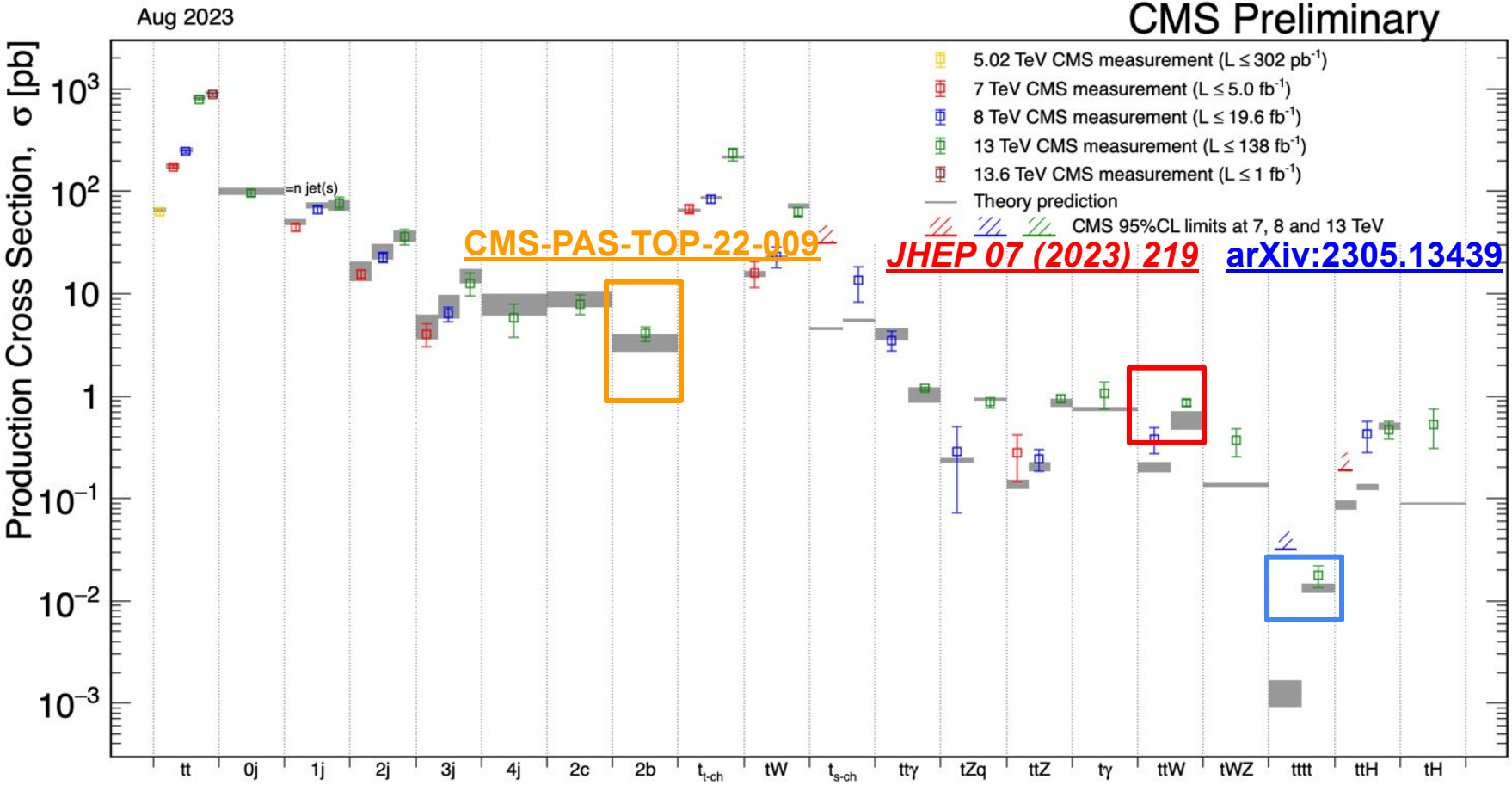
Introduction



- **Top quark: an unique particle**
- The most **massive** of all observed elementary particles
- The top quark is the only quark that has been directly **observed** due to its decay time being shorter than the hadronization time
- Top quark properties are studied extensively
- Very rich Top quark physics program from both collaborations:
  - Cross sections: top-antitop, single top, ttX, 4-top, …
  - Properties: mass, width, spin, charge…
  - Searches
- Today presenting latest results at CMS and ATLAS at 13 TeV
  - **4-top observation as a highlight**
  - Inclusive and differential ttW cross sections
  - Differential ttbb cross sections
  - Charge asymmetry at ttɣ

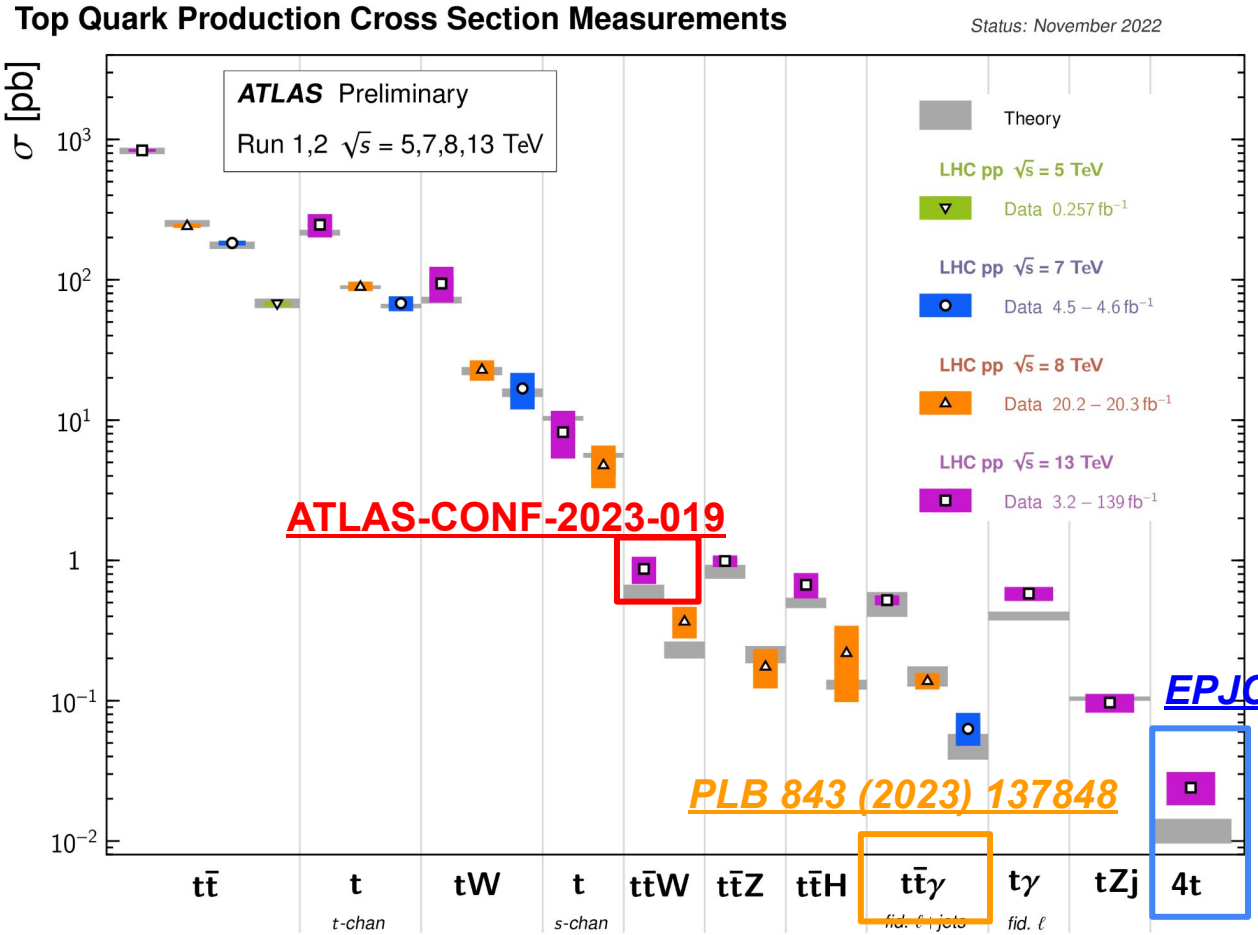


Latest ttX results from CMS

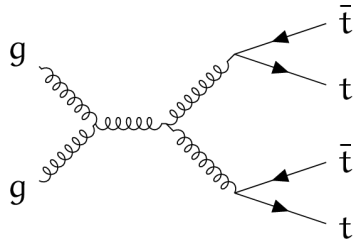


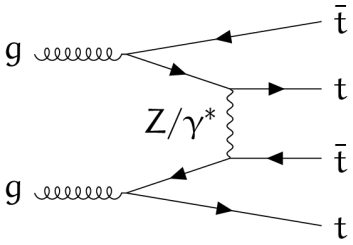
All results at: http://cern.ch/go/pNj7

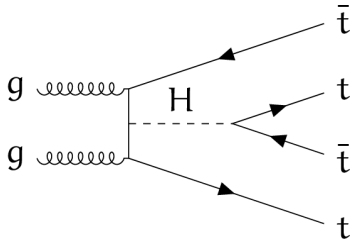
Latest ttX results from ATLAS



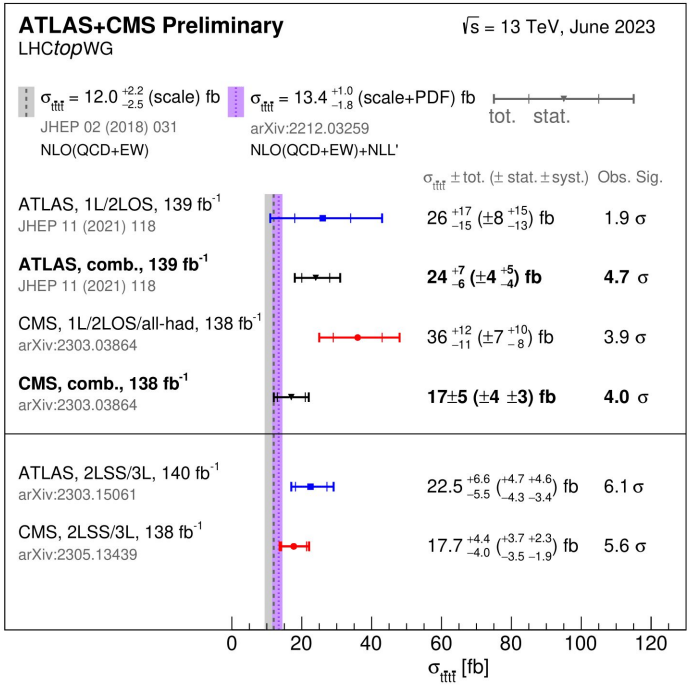
4-top Measurements: Introduction





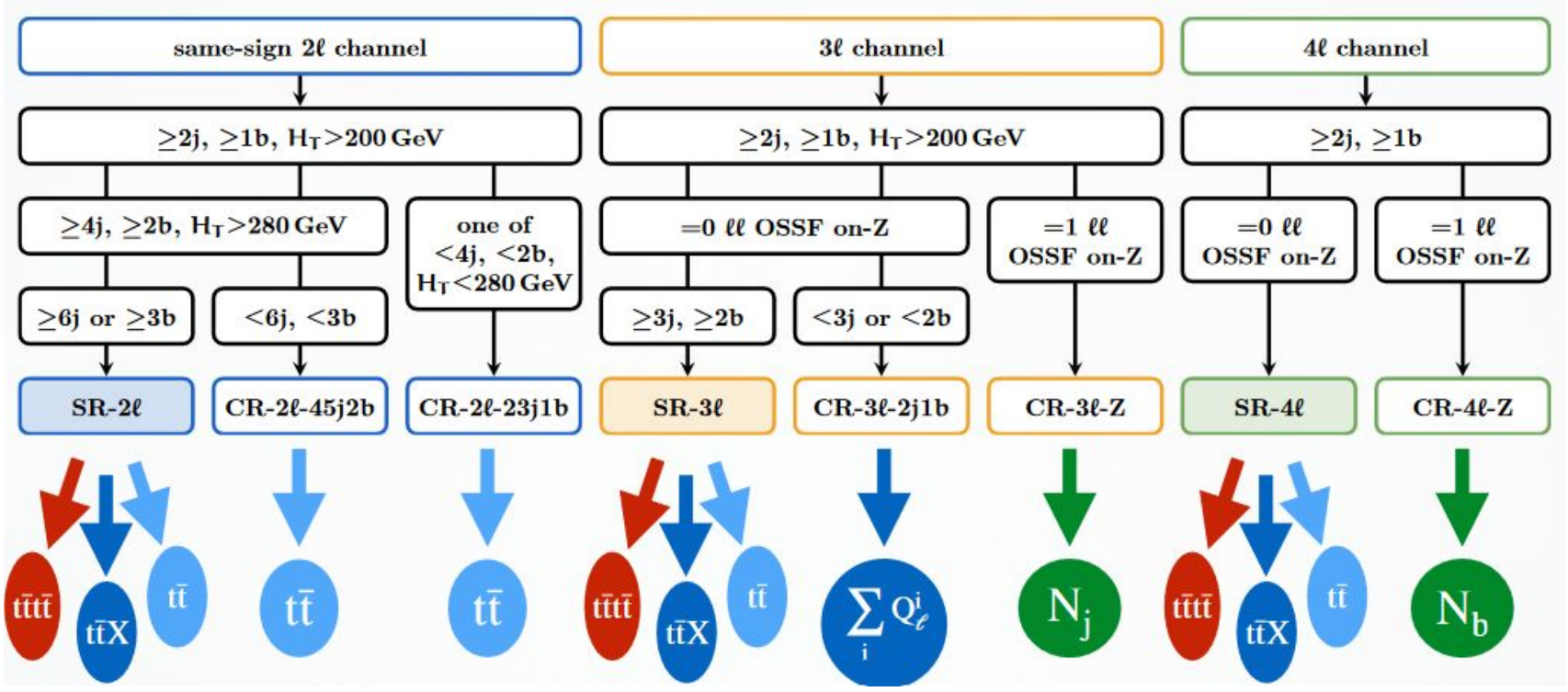


- **4-top production** is a **very rare process** sensitive to Higgs boson properties and BSM particles
- Production cross section *5 orders of magnitude smaller than top-antitop*: **~12 fb**
- Measured in multilepton on final states
- Both collaborations **have observed** the process now



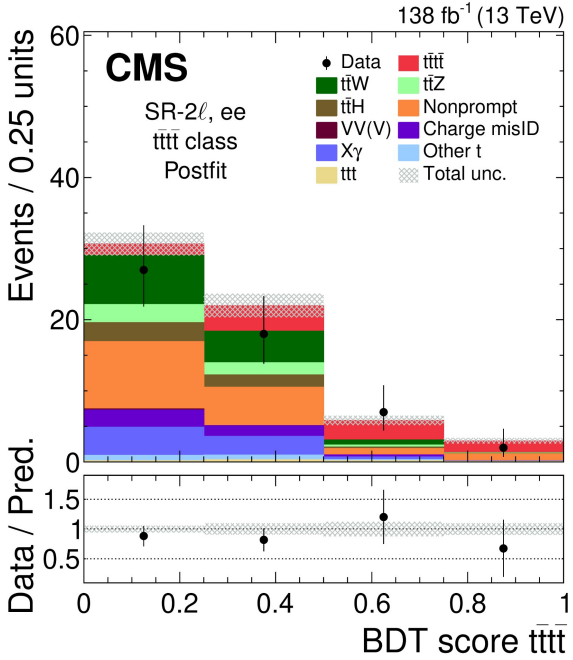
CMS 4-top: Event Selection and Categorization

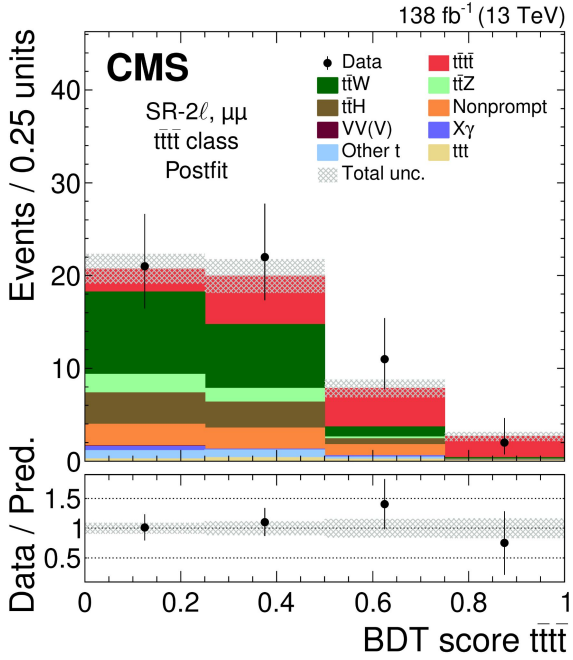
- Events with two same-sign (**2lss**), three (**3l**), or four (**4l**) charged leptons (*electrons and muons*) and additional jets
- Event categorization **based** on **jet** and **b-tagged jet** multiplicities, and $\mathbf{H_T}$

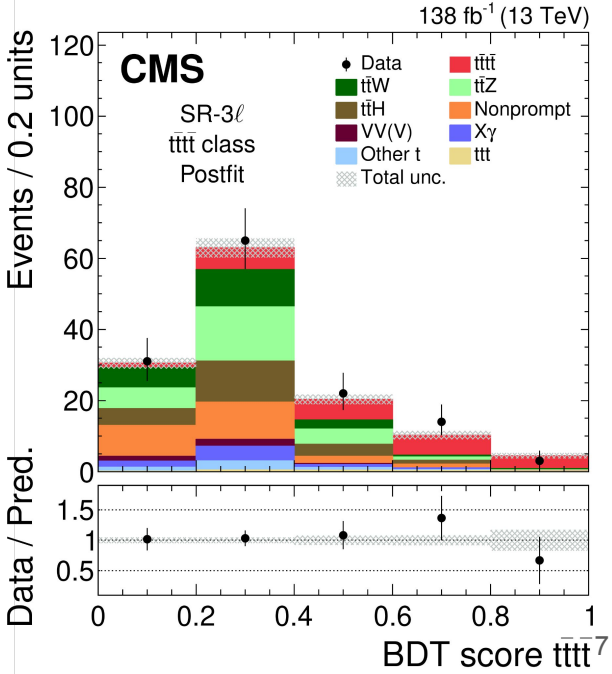


CMS 4-top: Analysis Strategy

- **Multivariate discriminants employed to:**
  - Identify **prompt leptons** and **b jets**
  - Distinguish between selected events from the **4-top signal** and the main background contributions: BDT outputs







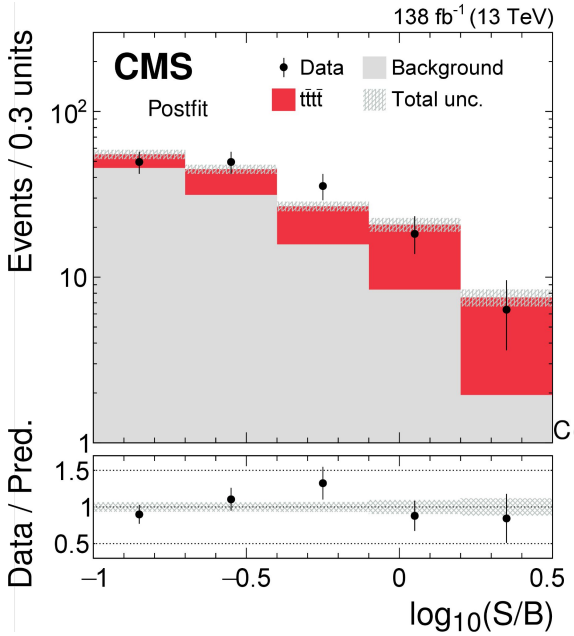
CMS 4-top: Results

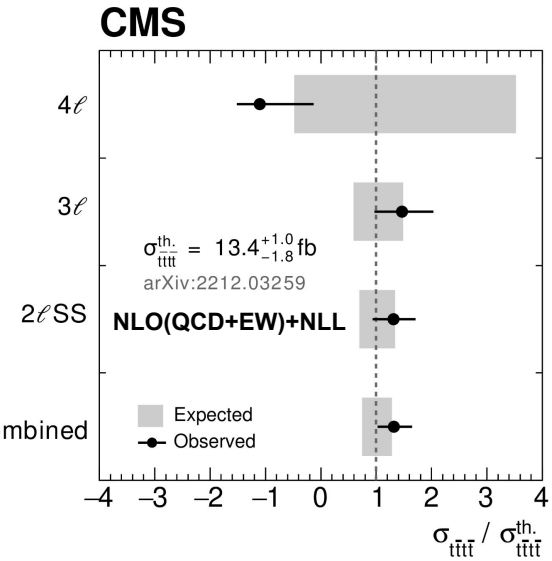
arXiv:2305.13439

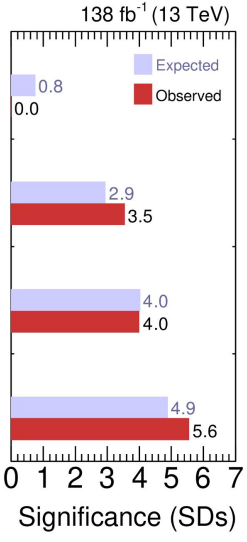
- Profile likelihood fit in SRs and CRs for the extraction of 4-top cross section
- The cross section is measured *in agreement with the SM predictions*

σ = 17.7 +3.7−3.5 (stat) +2.3−1.9 (syst) fb

- Significance of **5.6 standard deviations**
- **Leading uncert.:**
- b-tagging efficiency
- Jet energy scale
- ttW+(b)jets norm.
- ttZ normalization

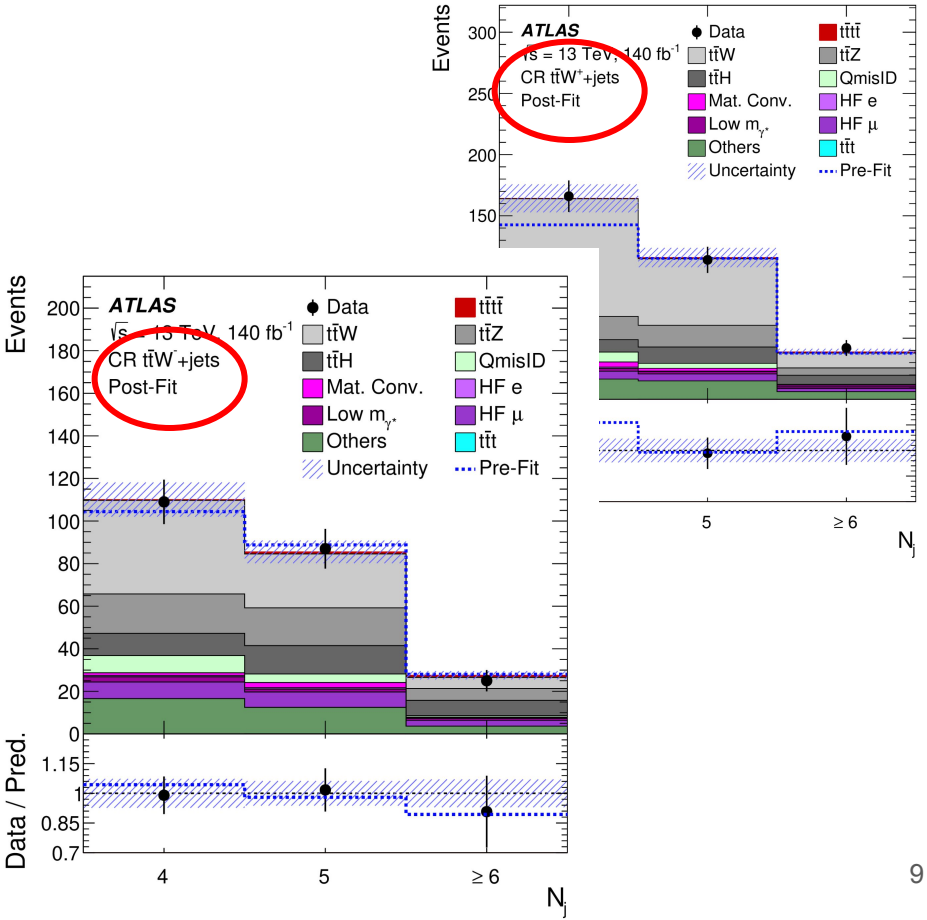






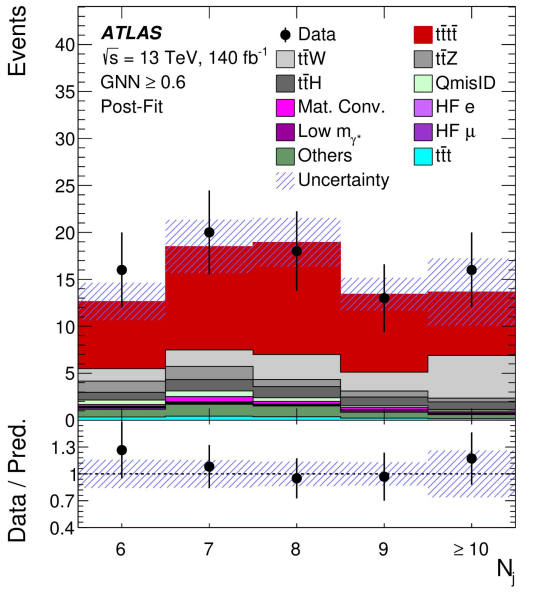
ATLAS 4-top: Event Selection and Categorization

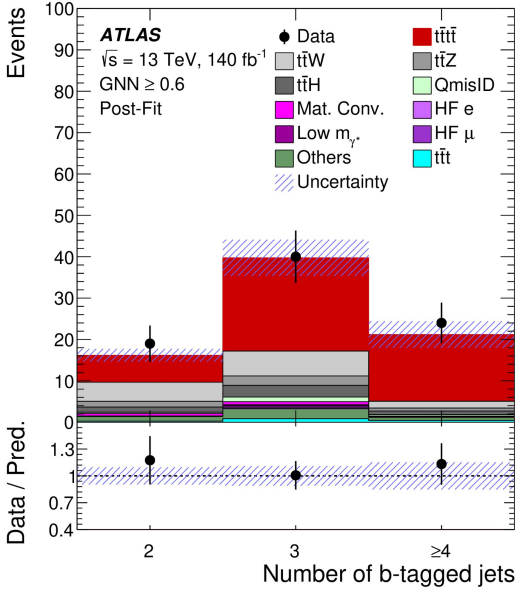
- Selection based on:
  - 2-3 charged lepton
  - Different requirements on jets and b-jets
  - Additional cuts on E_T^{miss} and H_T
- **SR:** 2Lss+3L $N_j \geq 6$, $N_b \geq 2$ and H_T
- **8 CRs** to control several backgrounds
- **Main backgrounds:**
  - **ttW+jets:** ***normalized from CRs***
  - ttZ+jets
  - ttH+jets

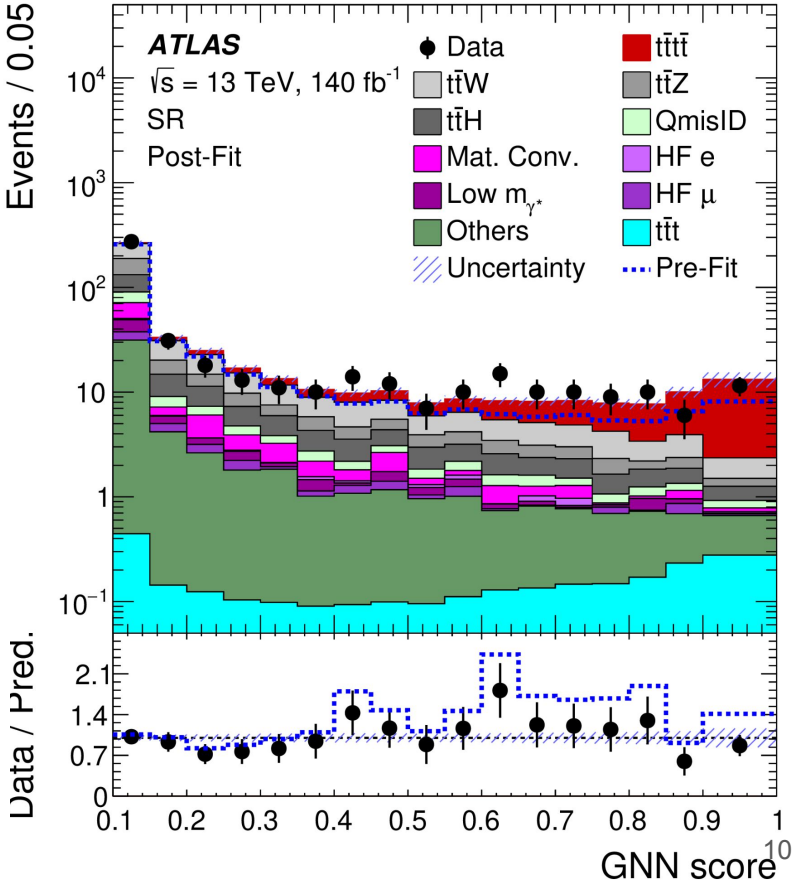


ATLAS 4-top: Analysis Strategy

- Use Graph Neural Network (**GNN**) to separate 4-top candidates from background
  - GNN adds 10% sensitivity compared to BDTs
- Study differential distributions for **GNN> 0.6**







ATLAS 4-top: Results

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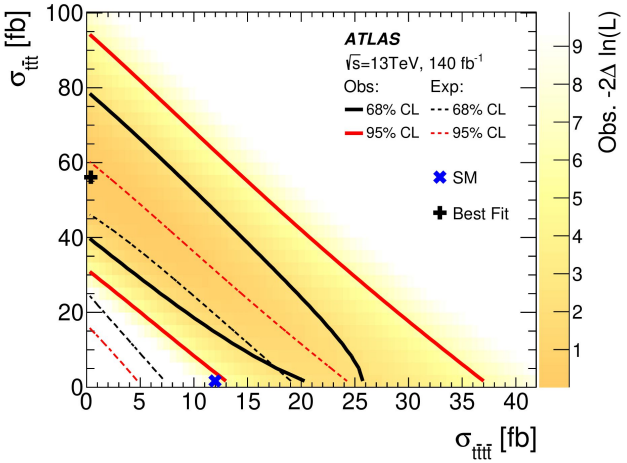
σ = 22.5+4.7−4.3 (stat) +4.6−3.4 (syst) fb = 22.5+6.6−5.5 (stat) fb

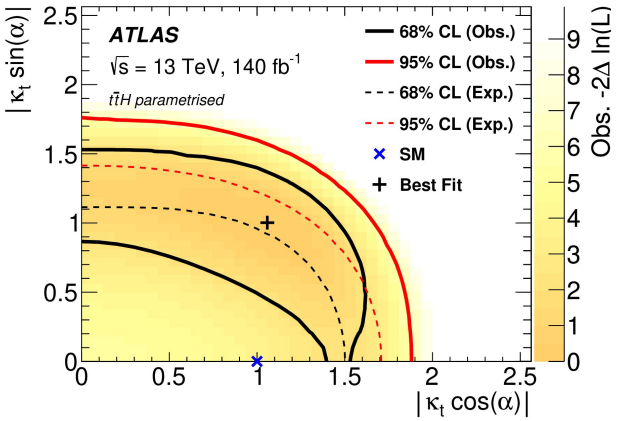
6.1 standard deviations

- **Leading sources of systematic uncertainty:**
  - 4-top Monte-Carlo generator choice and parton shower modelling
  - ttH+jets and ttW+jets theory modelling
  - Jet and b-jet related sources of uncertainty

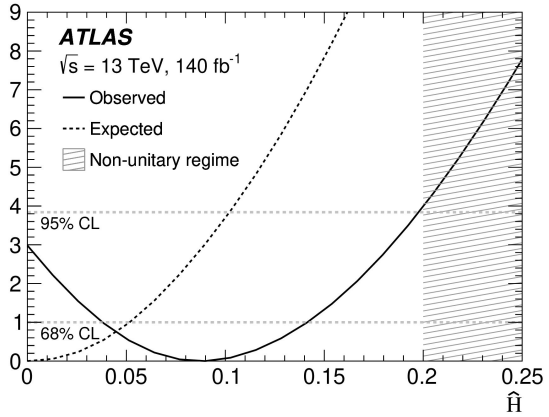
Compatible at 1.8 σ level with SM prediction



Measure independently 4-top and 3-top cross-sections



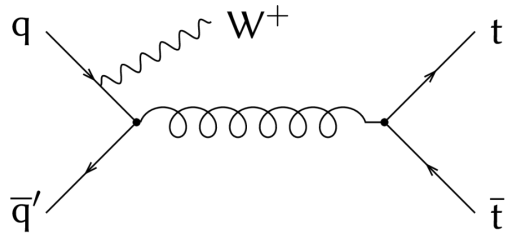
Probe for CP violating effects

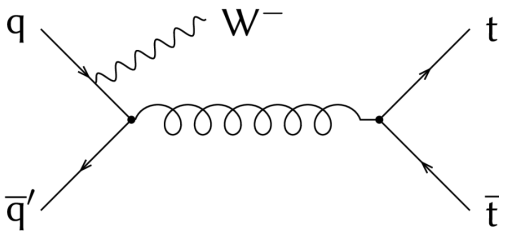


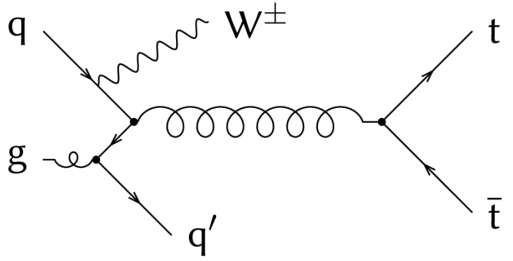
Set limits on the Higgs oblique parameter

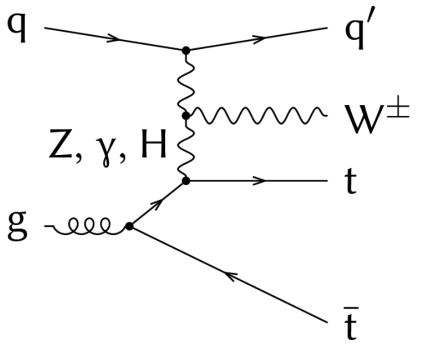
ttW Introduction

- Cross section consistently measured **above expectation**
- Theory production cross section at 13 TeV ≈ **0.7 pb**
- **Asymmetry** between ttW^+ and ttW^- (*no gg-initiated production*)
- Important **background** for many SM measurements: ***4-top, and ttH***



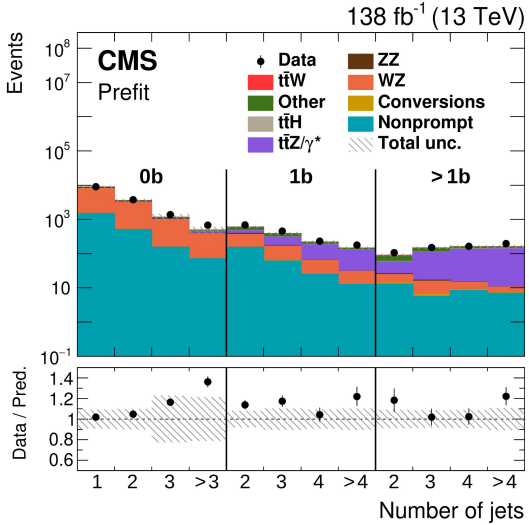


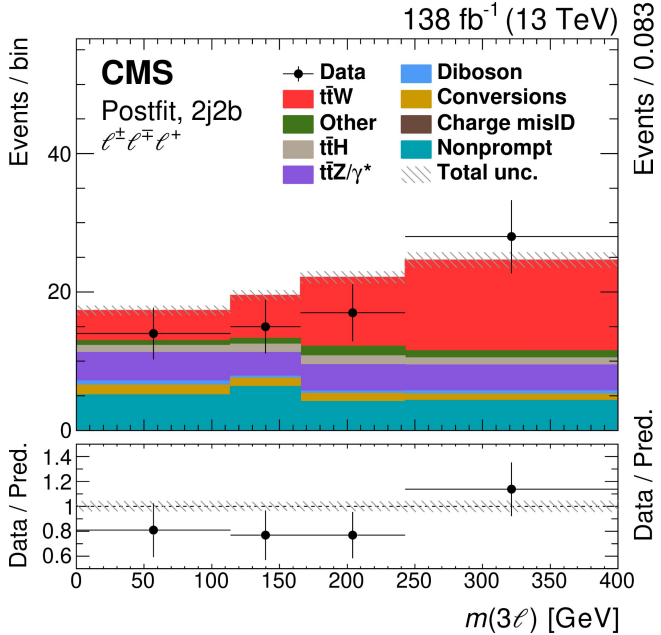


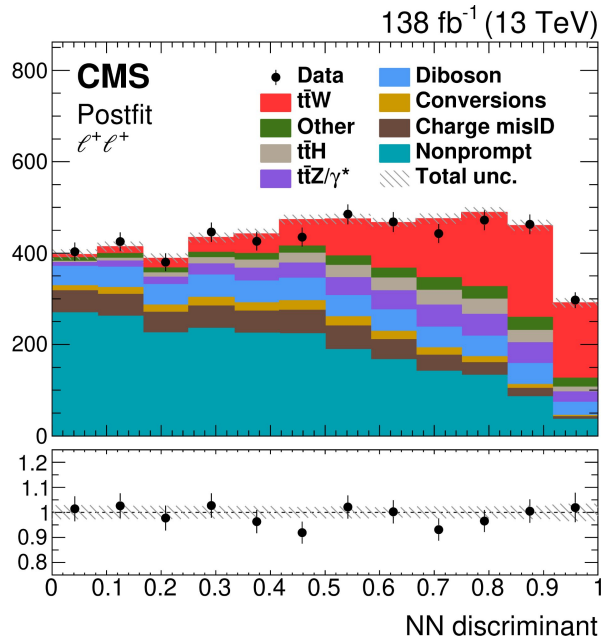


CMS ttW: Event Selection and Categorization

- Multilepton final states with b jet selection
- **2lss SR:** $N_j \geq 2$, N_b, *loose (tight)* ≥ 2 (1), $p_T^{miss} \geq 30$ GeV, $|m_{ee} - m_Z| > 15$ GeV → Apply **NN**
- **3l SR:** $N_j \geq 2$, N_b, *medium* ≥ 1, $|m_{ll} - m_Z| > 10$ GeV → event categorization on N_j, N_b, and lepton charges, and fit **m3l**
- **CRs:** 3/4 charged leptons







Profile likelihood fit of SR and CRs: NN (2lss), m3l (3l), number of jets and bjets (CRs)

CMS ttW: Results

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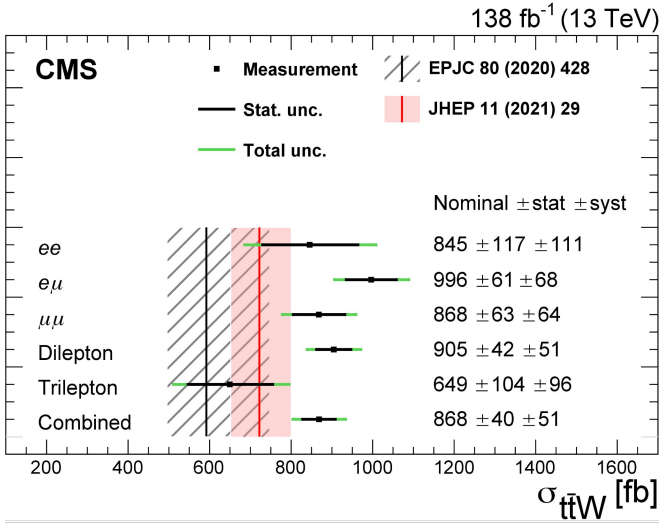
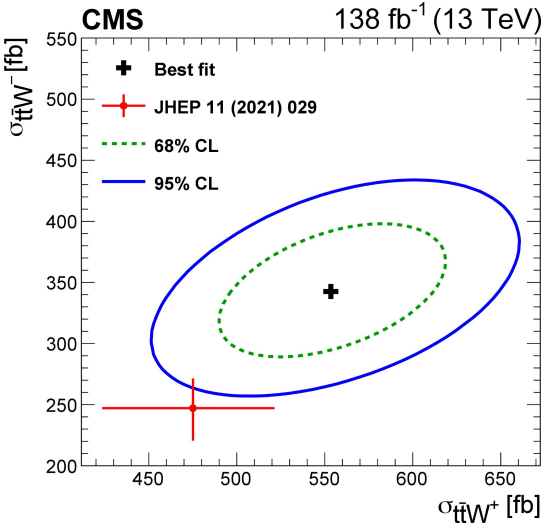
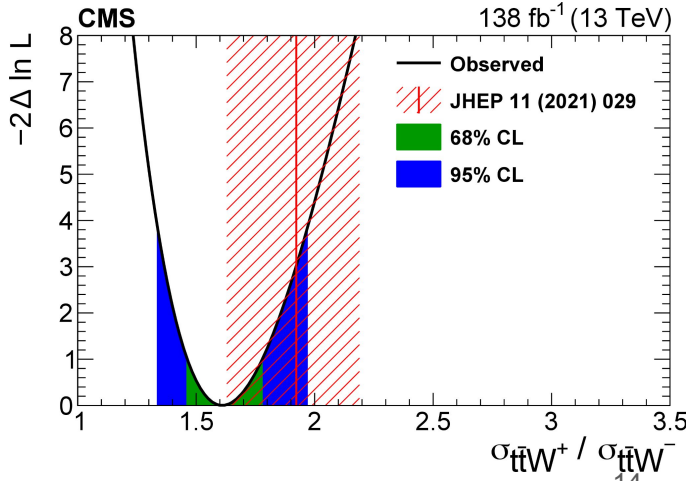
Observable	Measurement	SM prediction NLO + NNLL	SM prediction NLO + FxFx
$\sigma_{t\bar{t}W}$	$868 \pm 40\,(\text{stat}) \pm 51\,(\text{syst})$ fb	$592\,^{+155}_{-97}\,(\text{theo})$ fb	$722\,^{+71}_{-78}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W+}$	$553 \pm 30\,(\text{stat}) \pm 30\,(\text{syst})$ fb	$384\,^{+53}_{-33}\,(\text{theo})$ fb	$475\,^{+46}_{-52}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W-}$	$343 \pm 26\,(\text{stat}) \pm 25\,(\text{syst})$ fb	$198\,^{+26}_{-17}\,(\text{theo})$ fb	$247\,^{+24}_{-27}\,(\text{theo})$ fb
$\sigma_{t\bar{t}W+}/\sigma_{t\bar{t}W-}$	$1.61 \pm 0.15\,(\text{stat})\,^{+0.07}_{-0.05}\,(\text{syst})$	$1.94\,^{+0.37}_{-0.24}\,(\text{theo})$	$1.92\,^{+0.27}_{-0.29}\,(\text{theo})$

Compatible at 2σ level

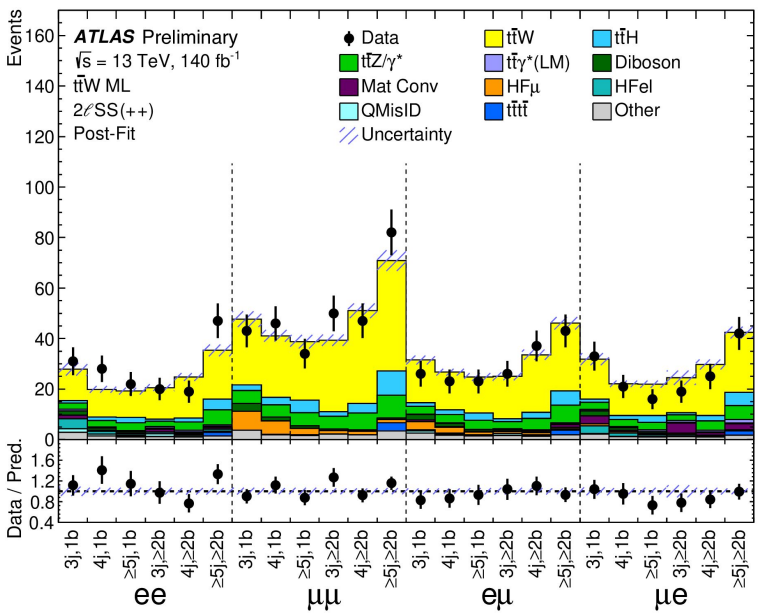


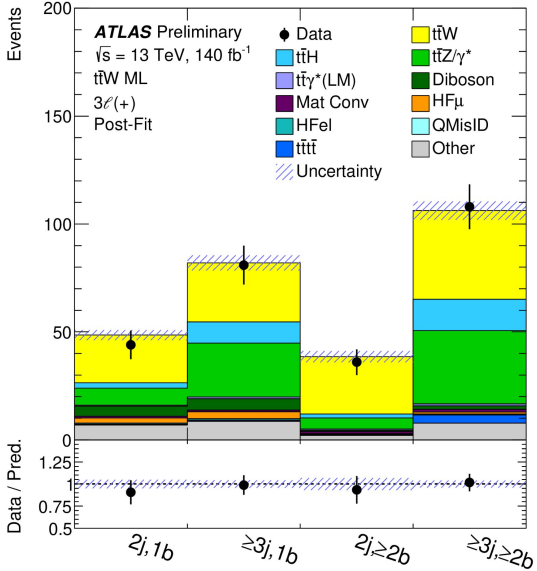


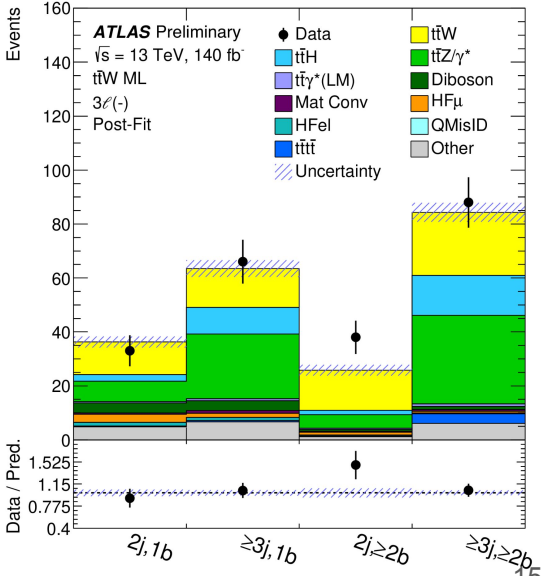


ATLAS ttW: Event Selection and Categorization

- Study events with 2LSS or 3L, plus ≥ 1 b-jet
- **Main backgrounds:**
  - ttZ and WZ +jets (normalised from corresponding CRs)
  - tt+jets events with mis-identified leptons
- Select signal candidates with b-jet and jet multiplicity bins







ATLAS ttW: Inclusive Results

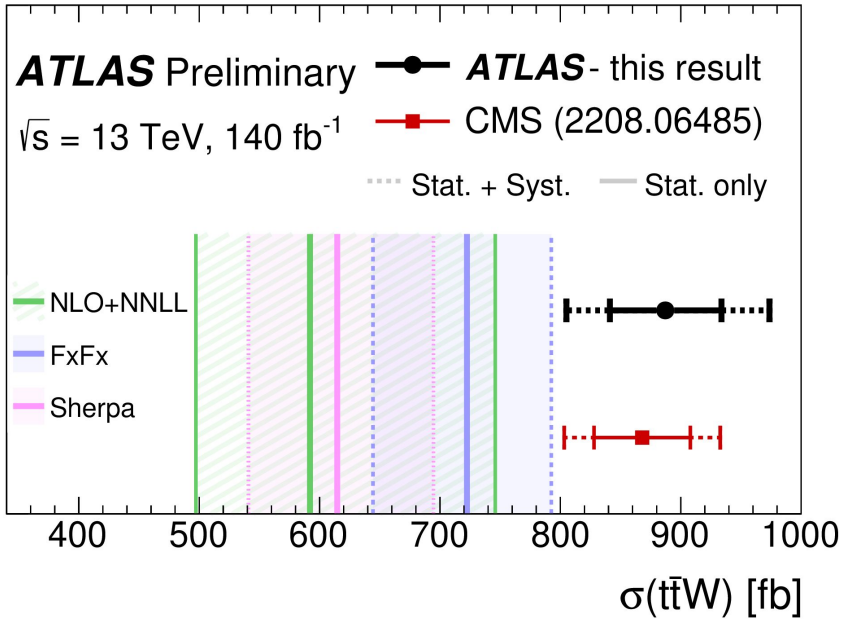
ATLAS-CONF-2023-019

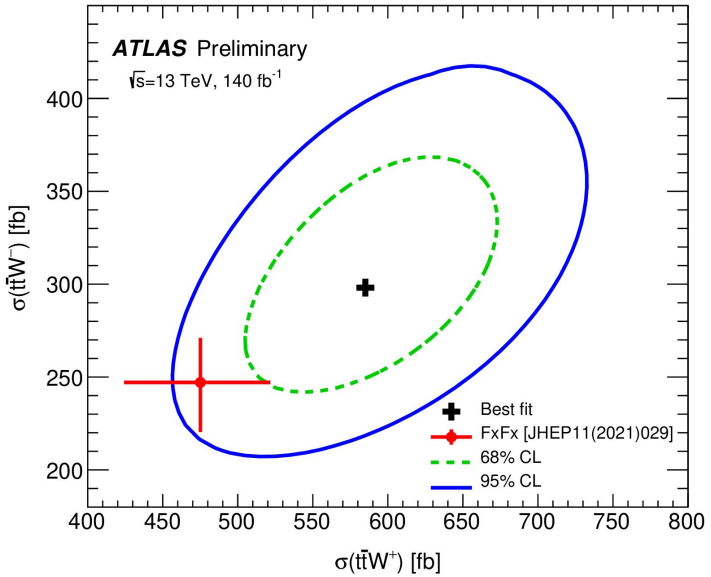
Measured total ttW cross section:

σ_{ttW} = 890 ± 50 (stat.) ± 70 (syst.) fb = 890 ± 80 fb

- **Leading sources of syst. uncertainty:**
  - ttW+jets modelling
  - ttZ and WZ normalisation
  - Backgrounds due to mis-identified leptons

Compatible at 1.5σ level with SM prediction



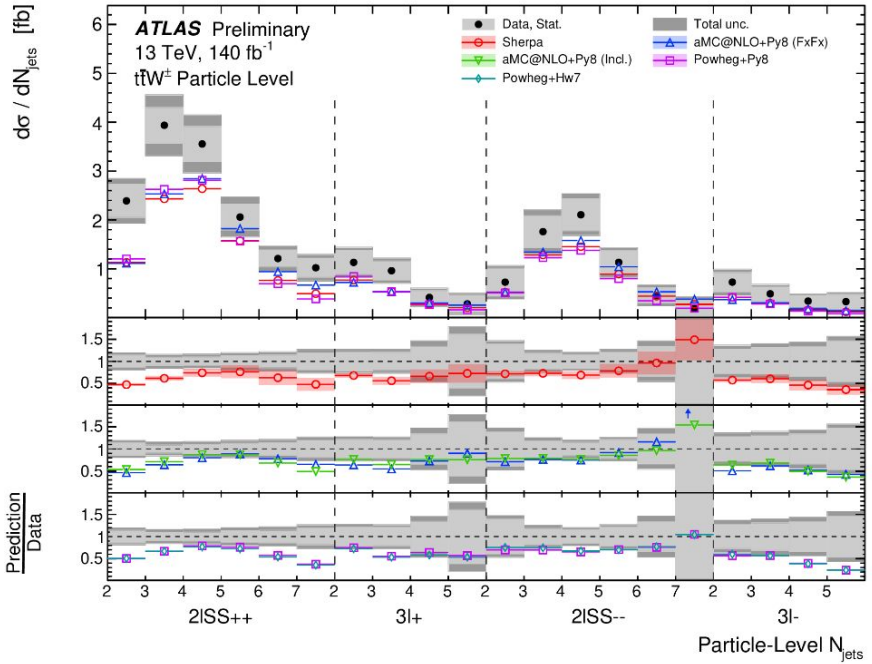


ATLAS ttW: Differential Results

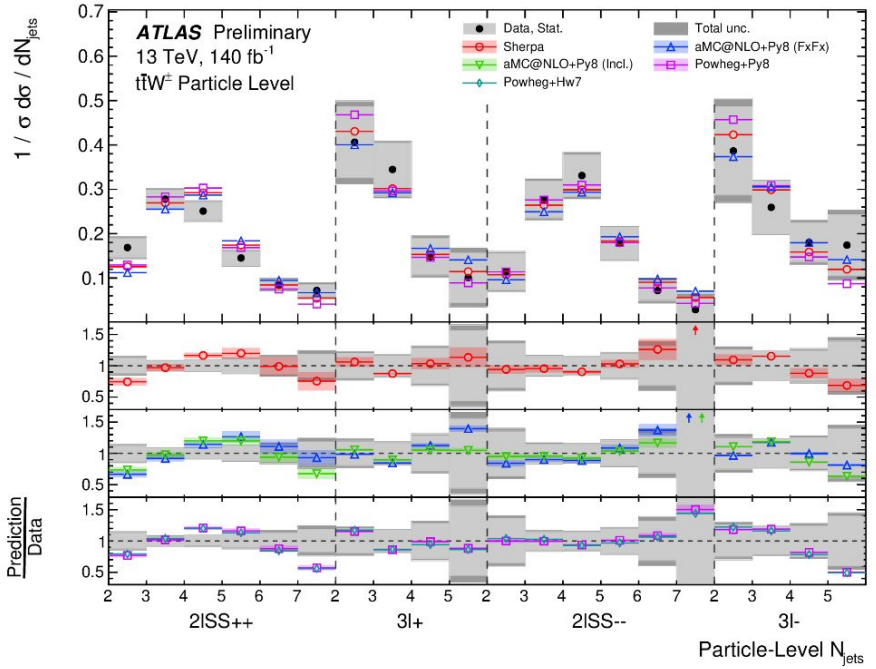
ATLAS-CONF-2023-019

Measured **particle level fiducial** cross-sections as a function of: *jet multiplicity, H_T, ΔR_{lb}, $|\Delta\phi_{ll,SS}|$, $|\Delta\eta_{ll,SS}|$, and $M_{jj,lead}$*

First ttW differential measurement



Fiducial absolute cross section



Fiducial normalized cross section

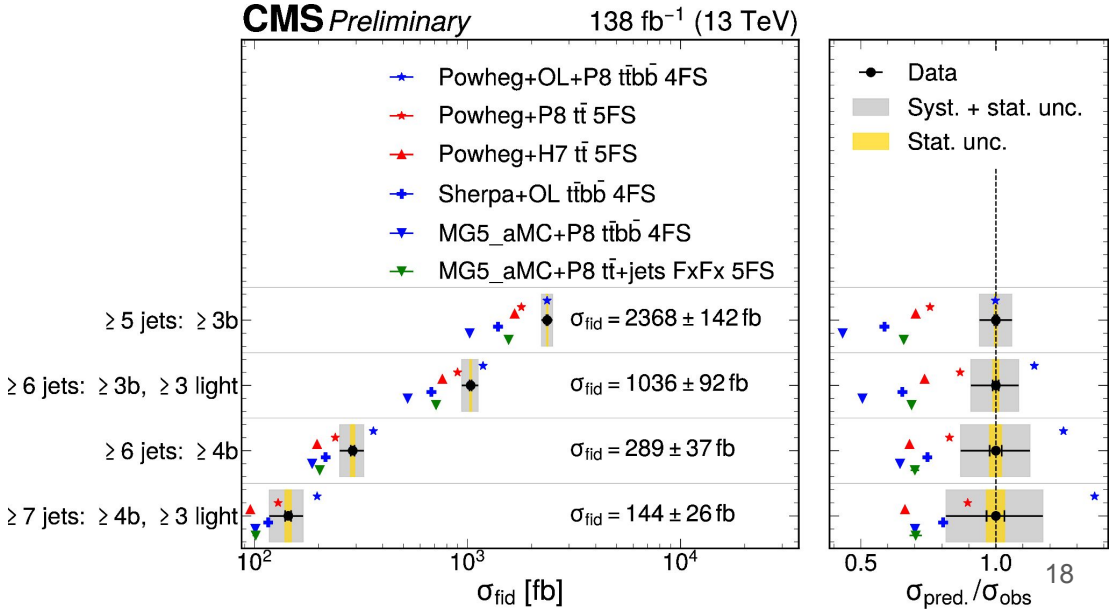
CMS ttbb: Inclusive cross section

CMS-PAS-TOP-22-009

- Events containing exactly **one lepton** and **at least five jets**
- Measurements in **4 fiducial phase space regions**, targeting different aspects of ttbb

Uncertainty source	5j3b	6j3b3l	6j4b	7j4b3l
Luminosity	1.6	1.6	2.0	1.7
Lepton and trigger	1.1	0.9	1.9	1.5
JES, JER	2.1	1.6	3.6	4.2
b tagging	4.5	3.9	7.0	9.0
Pileup	0.2	0.8	0.5	0.1
PDF	0.2	0.7	1.0	1.4
μ_R and μ_F scales	2.8	6.8	8.2	13
PS modelling	2.8	2.7	2.5	3.2
ttC normalization	0.5	0.3	1.9	2.7
Colour reconnection	1.1	1.5	1.9	2.7
Underlying event	0.4	0.9	1.3	2.7
h_{damp}	0.4	0.0	0.4	0.5
b fragmentation	0.1	0.1	0.6	1.2
Top p_T modelling	0.3	1.0	0.6	1.1
MC statistical	0.8	1.6	2.4	3.2
Total systematic uncertainty	6.0	8.7	13	18
Statistical uncertainty	0.6	1.2	2.2	3.4
Total uncertainty	6.0	8.8	13	18

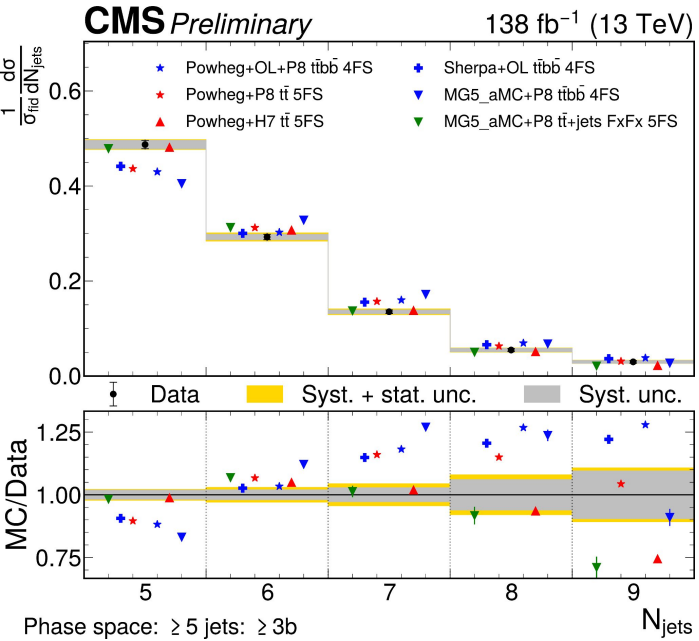
The **most precise measurements** of ttbb production up to date, **predicted** cross section **10-50% lower** than measured values

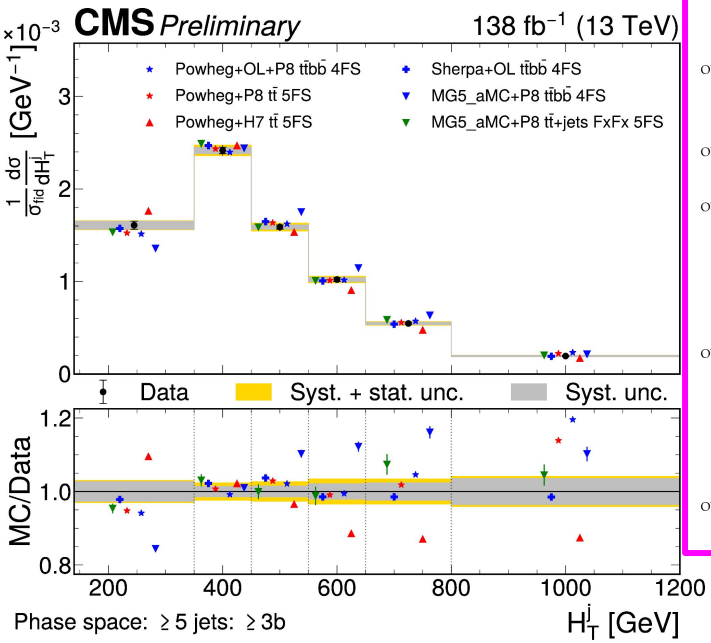


CMS ttbb: Differential cross section

CMS-PAS-TOP-22-009

- Distributions unfolded to the particle level through **maximum likelihood fits**, and compared with predictions from several event generators
- No generator **simultaneously** describes all the measured distributions





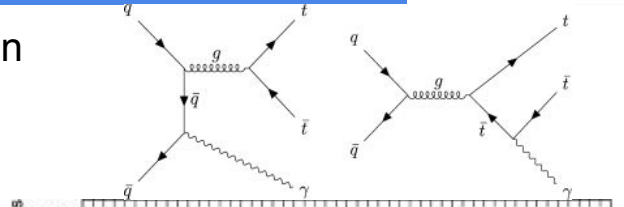
measured observables for each of the four fiducial phase space regions

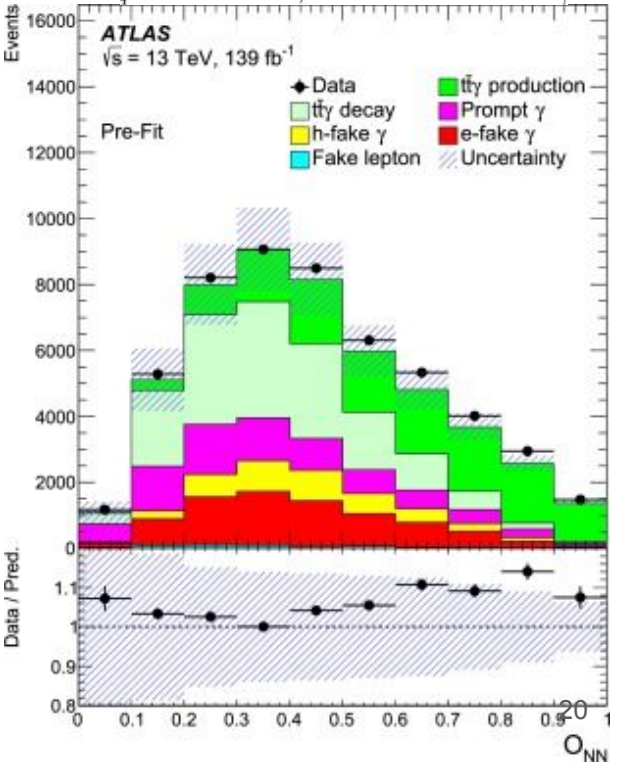
Observable		5j3b	6j4b	6j3b3l	7j4b3l
σ_{fid}	Inclusive cross section	✓	✓	✓	✓
Global observables					
N_{jets}	Jet multiplicity	✓	✓		
N_b	b jet multiplicity	✓			
H_T	Scalar sum of jet p_T	✓	✓		
H_T^b	Scalar sum of b jet p_T	✓	✓		
H_T^{light}	Scalar sum of light jet p_T			✓	✓
Observables related to b jets					
$p_T(b_3)$	p_T of third hardest b jet	✓	✓		
$\lvert\eta(b_3)\rvert$	$\lvert\eta\rvert$ of third hardest b jet	✓	✓		
$p_T(b_4)$	p_T of fourth hardest b jet		✓		
$\lvert\eta(b_4)\rvert$	$\lvert\eta\rvert$ of fourth hardest b jet		✓		
Observables considering all pairs of b jets (bb)					
ΔR_{bb}^{avg}	Average ΔR of all bb pairs		✓		
m_{bb}^{max}	Highest invariant mass among all bb pairs		✓		
Observables related to the pair of b jets closest in ΔR (bb^{extra})					
$p_T(b_1^{extra})$	p_T of leading extra b jet		✓		
$\lvert\eta(b_1^{extra})\rvert$	$\lvert\eta\rvert$ of leading extra b jet		✓		
$p_T(b_2^{extra})$	p_T of subleading extra b jet		✓		
$\lvert\eta(b_2^{extra})\rvert$	$\lvert\eta\rvert$ of subleading extra b jet		✓		
$\Delta R(bb^{extra})$	ΔR of bb^{extra} pair		✓		
$\lvert\eta\rvert(bb^{extra})$	$\lvert\eta\rvert$ of bb^{extra} pair		✓		
$m(bb^{extra})$	invariant mass of bb^{extra} pair		✓		
$p_T(bb^{extra})$	p_T of bb^{extra} pair		✓		
Observables related to the pair of b jets not from tt̄ decay ($bb^{add.}$)					
$p_T(b_1^{add.})$	p_T of leading additional b jet		✓*		
$\lvert\eta(b_1^{add.})\rvert$	$\lvert\eta\rvert$ of leading additional b jet		✓*		
$p_T(b_2^{add.})$	p_T of subleading additional b jet		✓*		
$\lvert\eta(b_2^{add.})\rvert$	$\lvert\eta\rvert$ of subleading additional b jet		✓*		
$\Delta R(bb^{add.})$	ΔR of $bb^{add.}$ pair		✓*		
$\lvert\eta\rvert(bb^{add.})$	$\lvert\eta\rvert$ of $bb^{add.}$ pair		✓*		
$m(bb^{add.})$	invariant mass of $bb^{add.}$ pair		✓*		
$p_T(bb^{add.})$	p_T of $bb^{add.}$ pair		✓*		
Observables related to extra light jets					
$p_T(lj_1^{extra})$	p_T of leading extra light jet			✓	✓
$\lvert\Delta\phi(lj_1^{extra}, b_{soft})\rvert$	$\Delta\phi$ of leading extra light jet and softest b jet			✓	✓

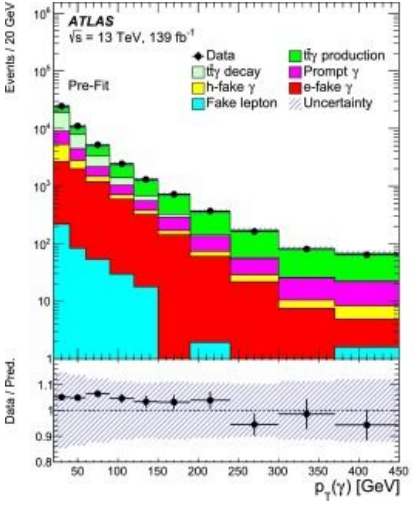
ATLAS ttɣ: Charge asymmetry

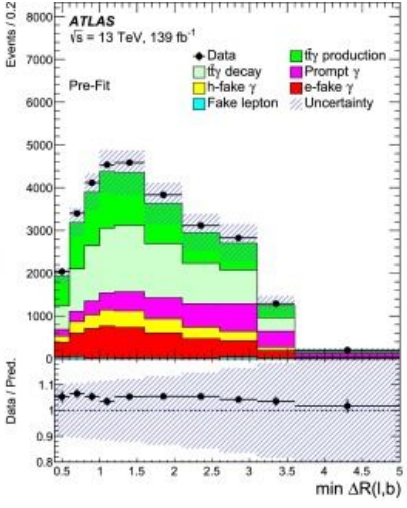
PLB 843 (2023) 137848

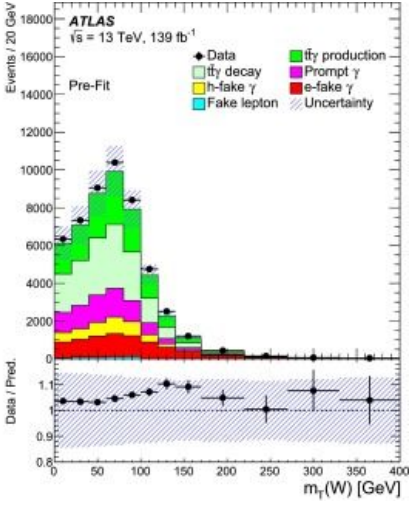
- The tt charge asymmetry enhanced in topologies where the fraction of **quark–antiquark-initiated production** is larger, such as in **ttɣ**
- Events containing **one lepton, one photon,** and **at least 4 jets**
- Separation between **signal** (*ttɣ production, ɣ* only from ttbar production) and **background** enhanced using a NN approach
- The output distribution of the NN is used to define two regions:
  - **NN< 0.6** enriched in **background events**
  - **NN> 0.6** enriched in **signal events**











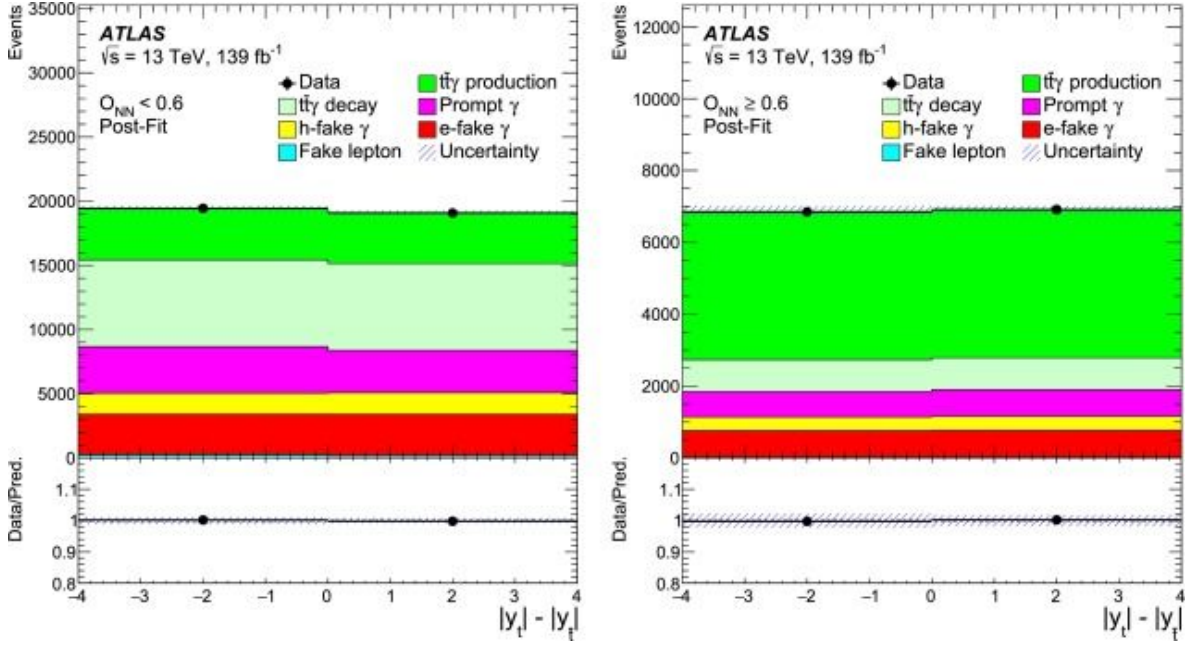
ATLAS ttγ: Charge asymmetry

PLB 843 (2023) 137848

- Obtained from the distribution of the difference of the absolute rapidities of the top quark and antiquark using a profile likelihood unfolding approach
- It is measured to be in agreement with the SM expectation

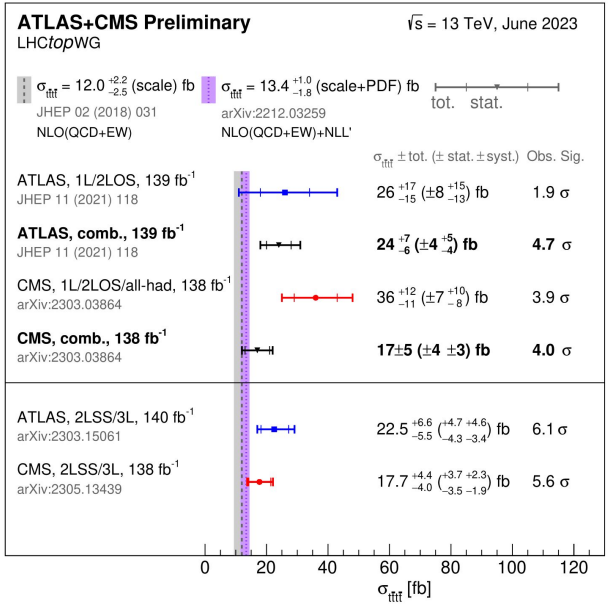
$$A_C = \frac{N(|y_t|>|y_{\bar{t}}|)-N(|y_t|<|y_{\bar{t}}|)}{N(|y_t|>|y_{\bar{t}}|)+N(|y_t|<|y_{\bar{t}}|)}$$

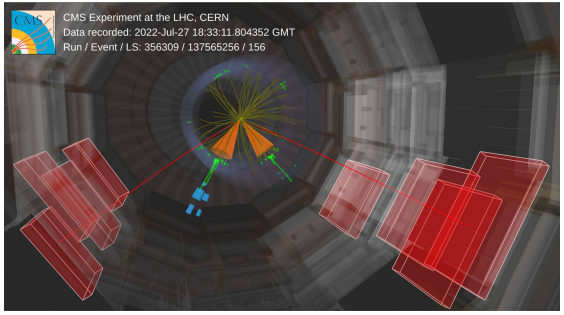
$$A_C = -0.003 \pm 0.029 = -0.003 \pm 0.024(\text{stat}) \pm 0.017(\text{syst})$$

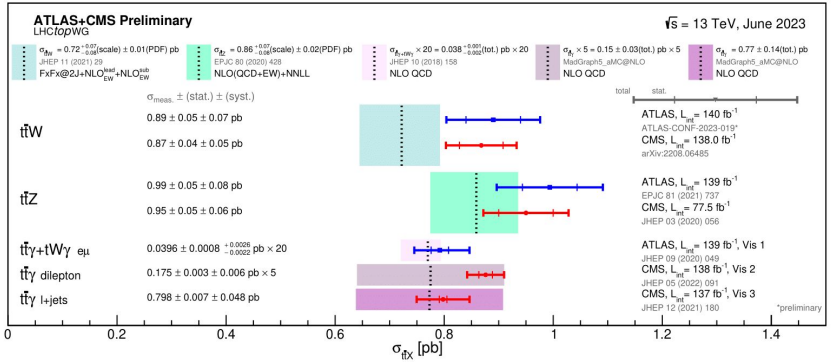


Summary

- Presented the **latest ttX** results from CMS and ATLAS collaborations
- Observation of **4-top** process with more than **5 σ significance**
- Measured **total and first differential** ttW cross-sections
- The **most precise measurements** of ttbb production up to date
- The **first measurement** of the charge asymmetry of the top-quark pairs in production in ttγ
- Measurements are **limited by systematic uncertainty**
- Stay tuned for updates with **Run-3 data**





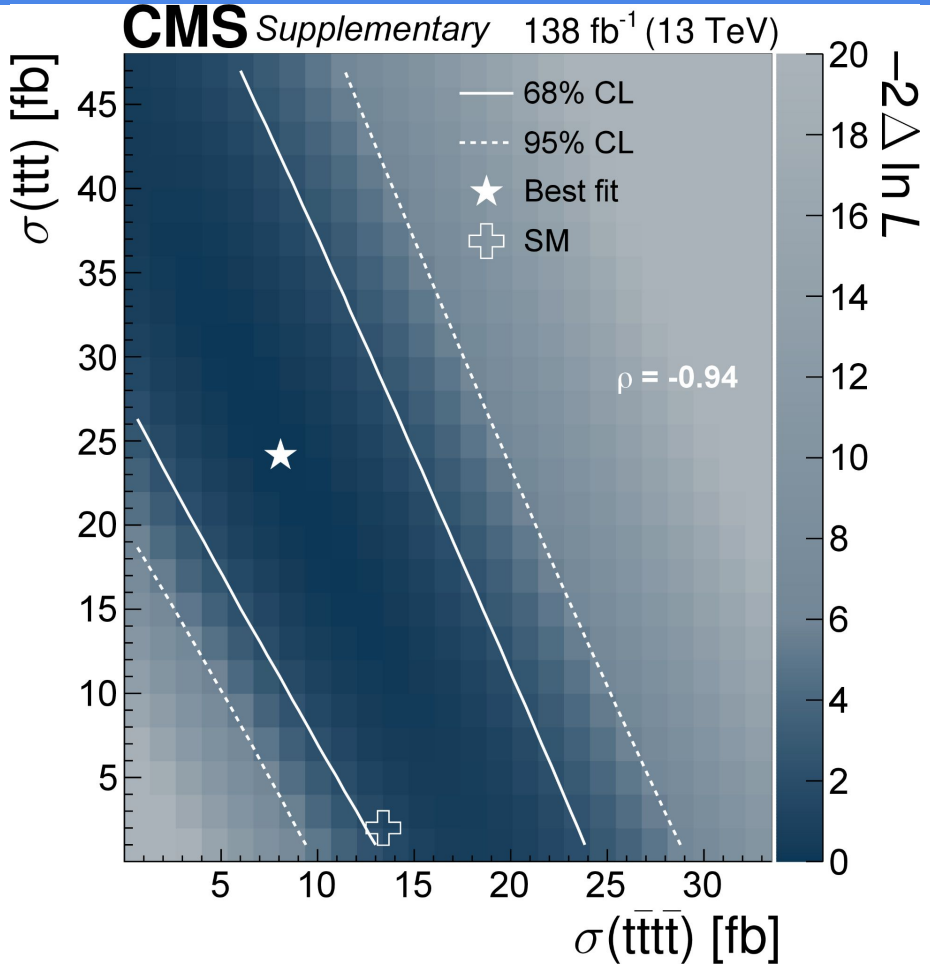


Latest ttX results from ATLAS and CMS

- 4-tops: Observation CMS and ATLAS arXiv:2305.13439 *EPJC 83 (2023) 496*
- ttW: Inclusive ttW cross section by CMS and inclusive, differential by ATLAS *JHEP 07 (2023) 219* ATLAS-CONF-2023-019
- ttbb by CMS CMS-PAS-TOP-22-009
- ttgamma by ATLAS *PLB 843 (2023) 137848*

CMS 4-top: Results

arXiv:2305.13439



ATLAS 4-top: Event Selection and Categorization

- Select 2lss and 3l charged lepton events with ≥ 1 b-jet
- **Main backgrounds:**
  - **ttW +jets:** ***normalized from CRs***
  - ttZ+jets
  - ttH+jets

Region	Channel	N_j	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \le N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from virtual photon (γ^*) decay ℓ_1 and ℓ_2 are not from photon conversion	counting
CR Mat. Conv.	SS, ee or eμ	$4 \le N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from photon conversion	counting
CR HF μ	e$\mu\mu$ or $\mu\mu\mu$	≥ 1	$= 1$	$100 < H_T < 300$ GeV $E_T^{miss} > 50$ GeV total charge = ± 1	$p_T^{\ell_3}$
CR HF e	eee or eeμ	≥ 1	$= 1$	$100 < H_T < 275$ GeV $E_T^{miss} > 35$ GeV total charge = ± 1	$p_T^{\ell_3}$
CR $t\bar{t}W^+$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \ge 3$: $H_T < 500$ GeV total charge > 0	N_j
CR $t\bar{t}W^-$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \ge 3$: $H_T < 500$ GeV total charge < 0	N_j
CR 1b(+)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_T > 500$ GeV total charge > 0	N_j
CR 1b(-)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_T > 500$ GeV total charge < 0	N_j
SR	2LSS+3L	≥ 6	≥ 2	$H_T > 500$ GeV	GNN score