tt+X measurements at ATLAS and CMS

TOP2022 - 15th International Workshop on Top-Quark Physics

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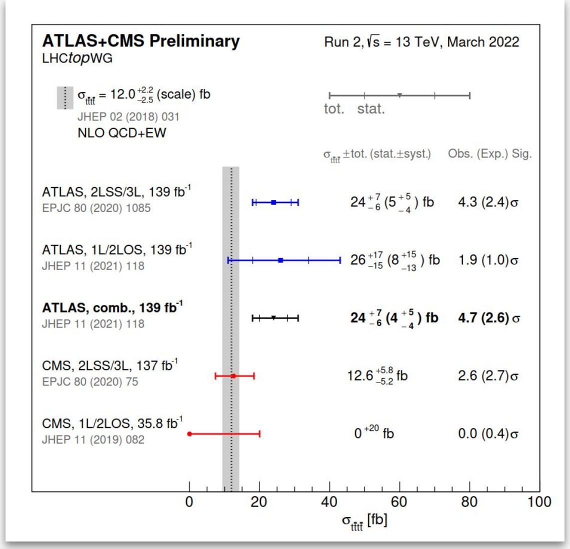
on behalf of the ATLAS and CMS Collaborations

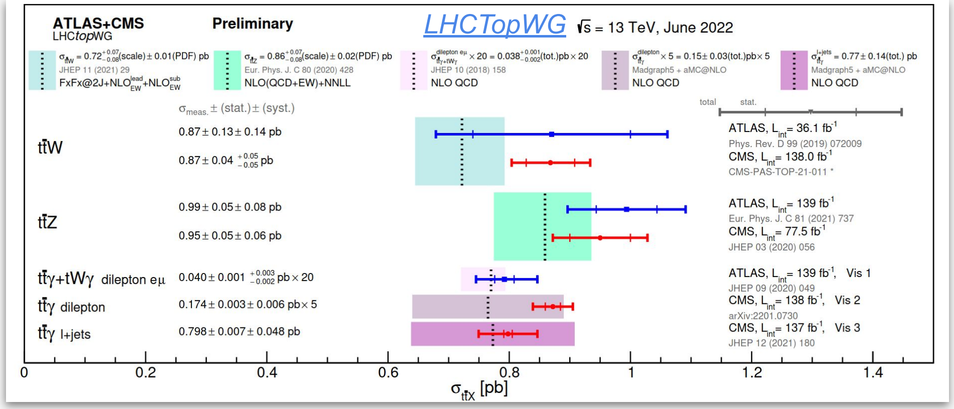
Supported by the Doctoral School "Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology"

tt+X measurements

- ❑ High precision **inclusive/differential measurements of tt+γ/Z/W**
  - ➢ High purities in lepton-dominated final states
  - ➢ Most lepton channels covered by ATLAS+CMS in RunII

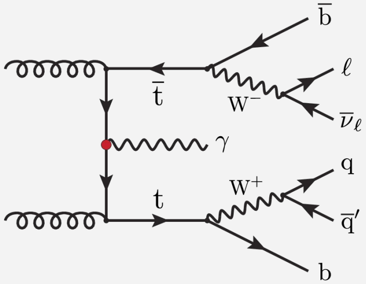


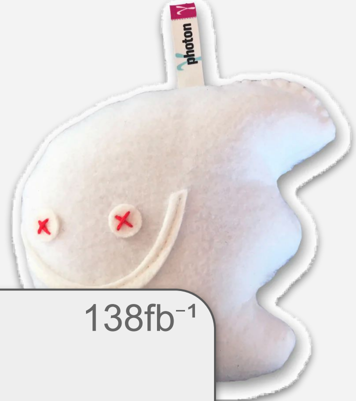
- ❑ Searches for **four top production**
  - ➢ Low cross-section
  - ➢ Often difficult background (tt+heavy flavor, ttW)
  - ➢ Good coverage by ATLAS+CMS in RunII



- ❑ Measurements of tt+heavy flavor
  - ➢ Important background (tttt and ttH)
  - ➢ Not covered today

tt+γ





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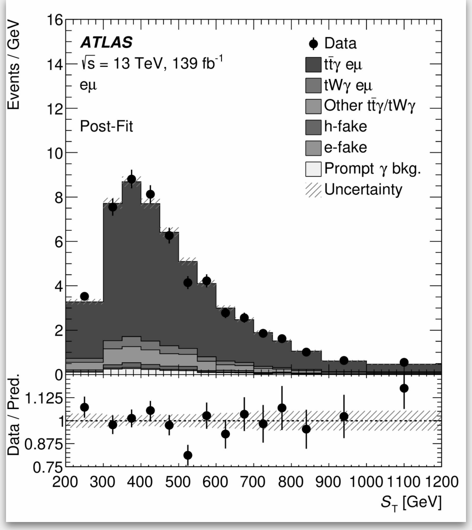
ttγ+tWγ eμ: JHEP 09 (2020) 049



ttγ 2ℓ: JHEP 05 (2022) 091

ttγ 1ℓ: JHEP 12 (2021) 180

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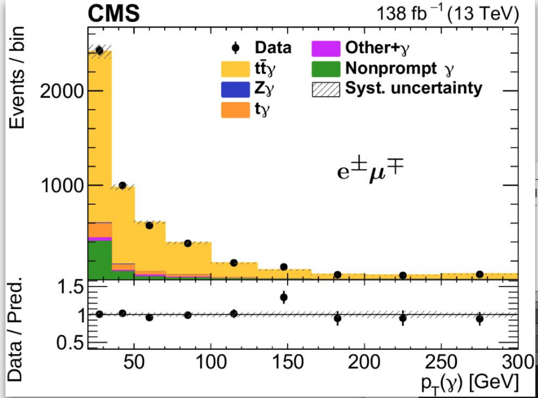
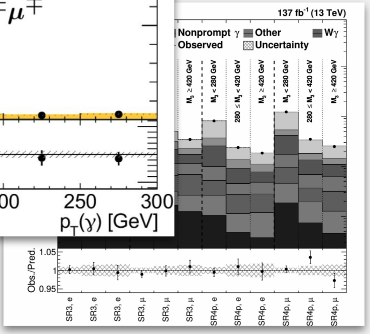
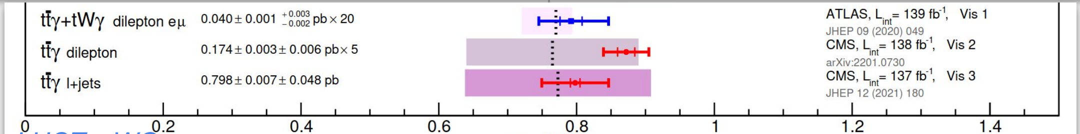






LHCTopWG

Also covered in EFT talk by Jon Wilson (Tuesday)

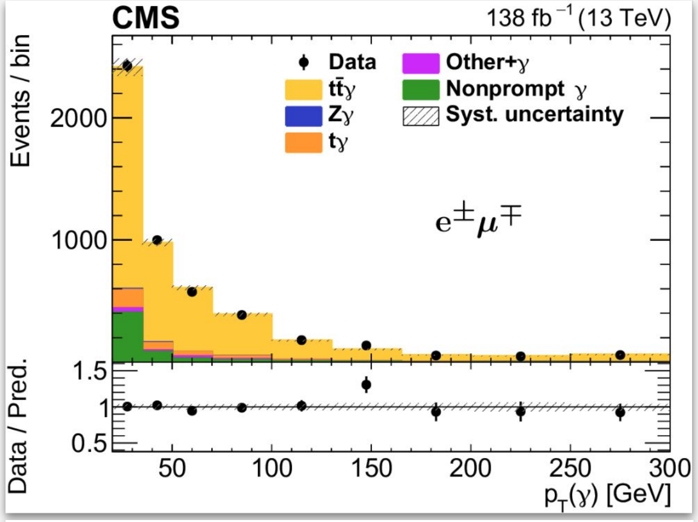
tt+γ cross section measurement (CMS)

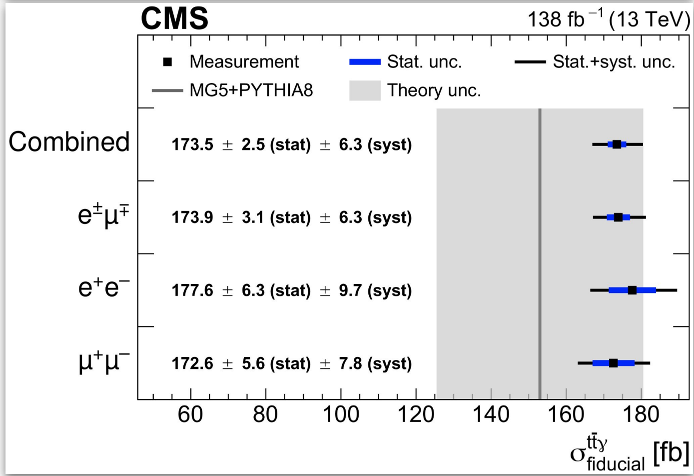
- Measurement of **ttγ in OS2ℓ channel**
- Fiducial region at particle level:
  - 2 leptons (ee/μμ/eμ), ≥1 b-jet, one γ
- Fit $p_T(\gamma)$ distribution for inclusive cross-section

- Backgrounds:
  - non-prompt γ → data-driven estimation
  - Zγ → CR on Z peak
  - Others (e.g. tγ) estimated from simulation

- Observed: **σ(ttγ) = 175.2 ± 2.5(stat) ± 6.3(syst) fb**
  - Precision of 4%
  - Dominated by luminosity, signal modeling, background normalization

- Agrees well with prediction (MG5aMC)
  σ(ttγ) = 155 ± 27 fb (LO sim. + NLO k factor)
  - Slight underprediction possibly due to importance of γ in NLO calculations (JHEP 03 (2020) 154)



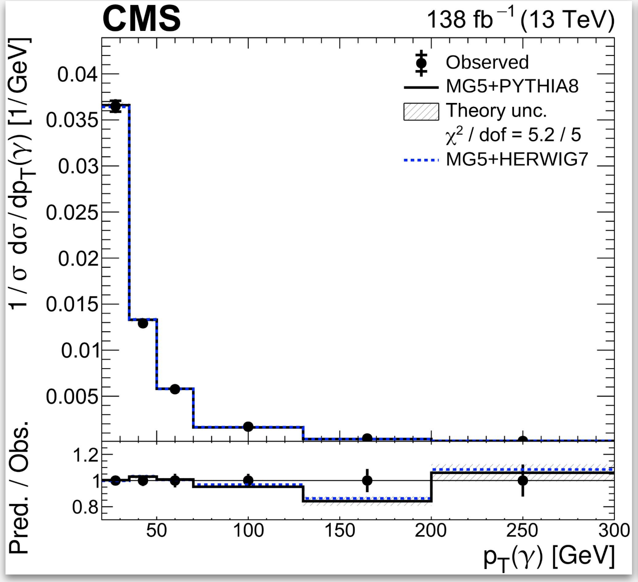


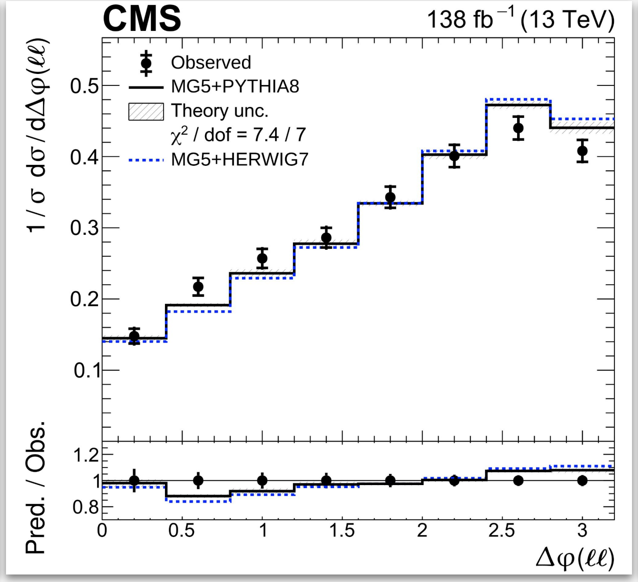
CMS ttγ 2ℓ: JHEP 05 (2022) 091

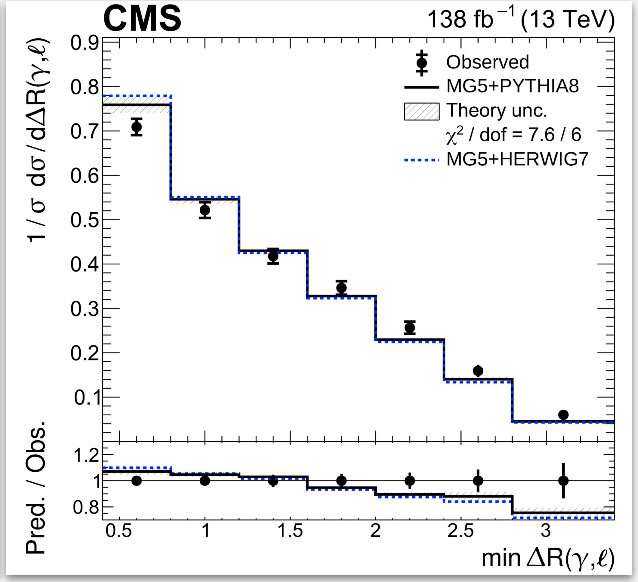
Also covered in EFT talk by Jon Wilson (Tuesday)

tt+γ cross section measurement (CMS)

- Differential measurement via unfolding to particle level with TUnfold
- Photon kinematics well-described by MG5aMC simulations
- Some trends in lepton observables and lepton+γ observables
  - ➢ Hints on mismodelling of γ origin in MG5aMC simulation







CMS ttγ 2ℓ: *JHEP 05 (2022) 091*

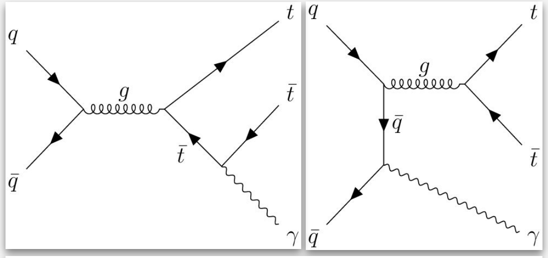
Charge asymmetry in tt+γ (ATLAS)

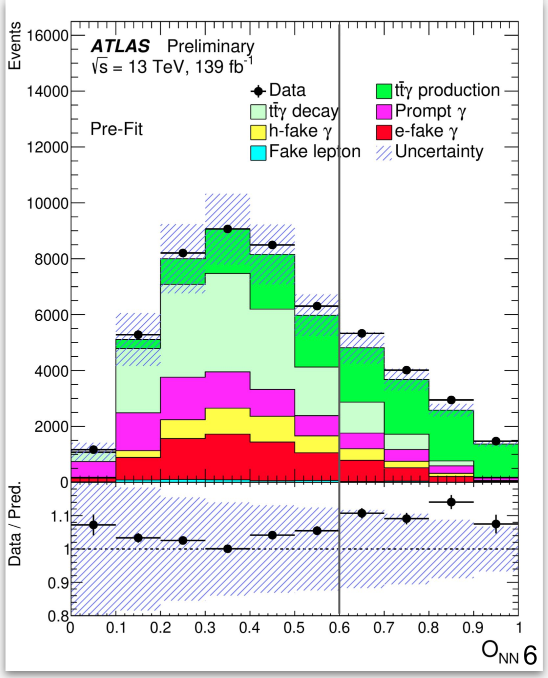
Also covered in ML talk by Philip Keicher (Friday)

Dedicated Poster by Amartya Rej (Monday)

NEW! 139fb^{-1}

- Probe **charge asymmetry of top quarks and antiquarks**
  - ➢ Symmetrical in LO tt, small asymmetries from qq→tt
  - ➢ Enhanced in initial-state γ radiation (+interference)
  - ➢ Diluted by symmetrical γ from tt decay
- Signal definition:
  - ➢ only ttγ production; decay is background
  - ➢ Single lepton channel
- Employ DNN to identify ttγ production
  - ➢ Used to split phase space in SR / CR
- Backgrounds:
  - ➢ Fake γ → estimated on Z peak / photonID inversion
  - ➢ Non-prompt → data-driven from loose leptonID region
  - ➢ Prompt γ and ttγ decay estimated from simulation





ATLAS ttγ charge asymmetry: *ATLAS-CONF-2022-049*

Charge asymmetry in tt+γ (ATLAS)

Also covered in ML talk by Philip Keicher (Friday)

Dedicated Poster by Amartya Rej (Monday)

NEW! 139fb^{-1}

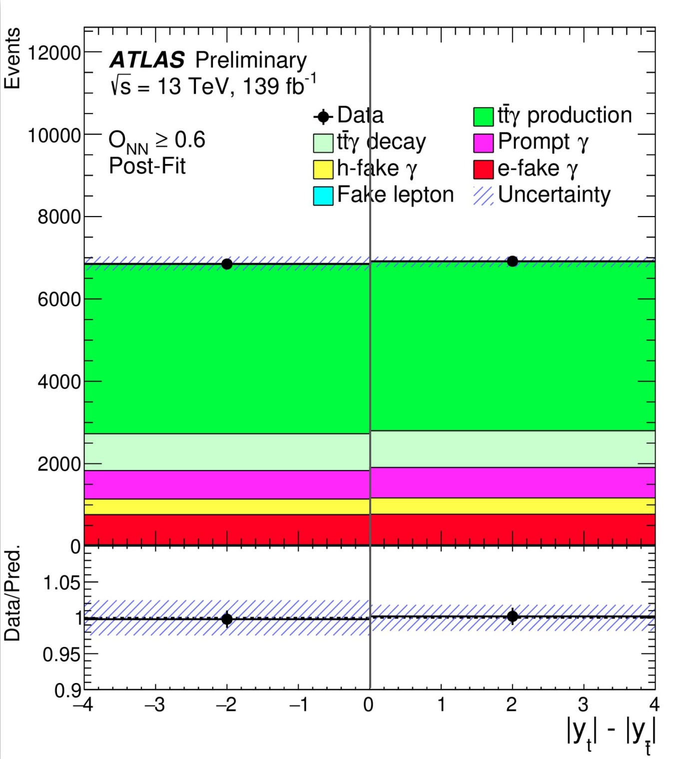
- Probe **charge asymmetry of top quarks and antiquarks**
  - Construct asymmetry from top quark/antiquark rapidity

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

- Kinematic reconstruction of top quark pair
  - Fit performed in two bins of $|y_t|-|y_{\bar{t}}|$ (Top quark or antiquark rapidity higher)

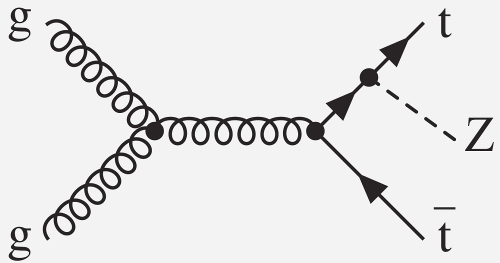
- Observed: **A_C= −0.006 ± 0.024(stat) ± 0.018(syst)**
  - Limited by data and MC statistics
- Agrees well with prediction (MG5amC)

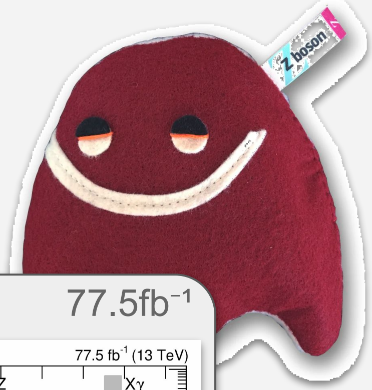
A_C= −0.014 ± 0.001(scale)



ATLAS ttγ charge asymmetry: *ATLAS-CONF-2022-049*

tt+Z





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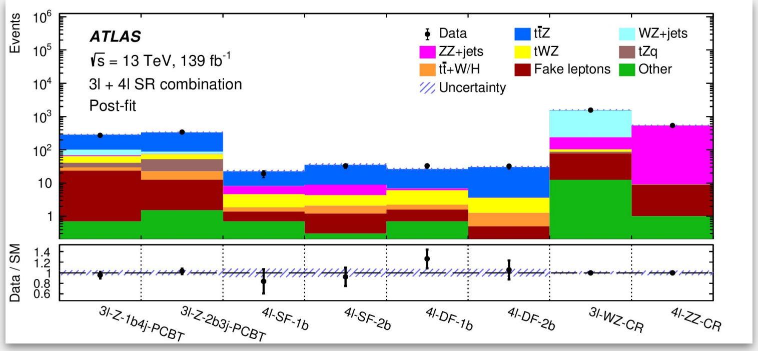
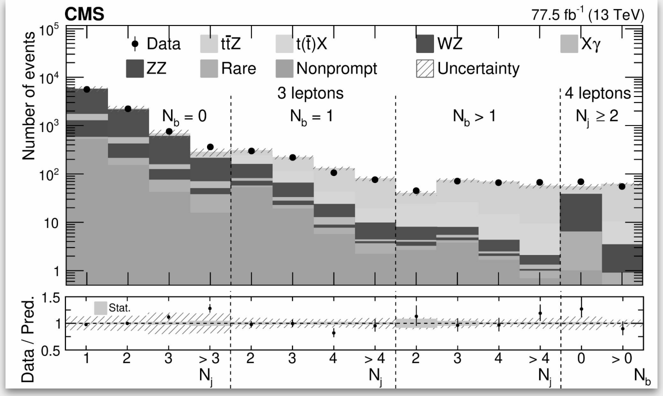
ttZ 3ℓ/4ℓ: EPCJ 81 (2021) 737



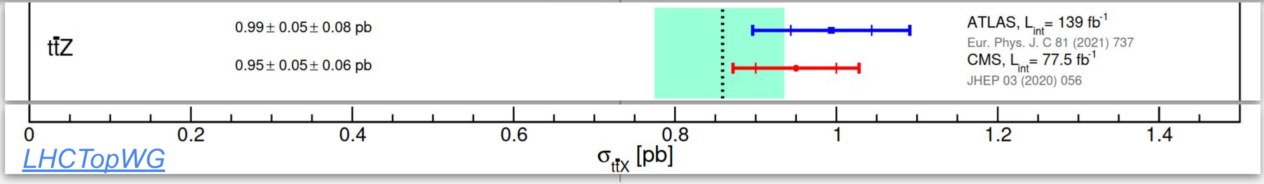
σ(ttZ) = 0.99 ± 0.05(stat) ± 0.08(syst) pb

ttZ 3ℓ/4ℓ: JHEP 03 (2020) 056

77.5fb^{-1}



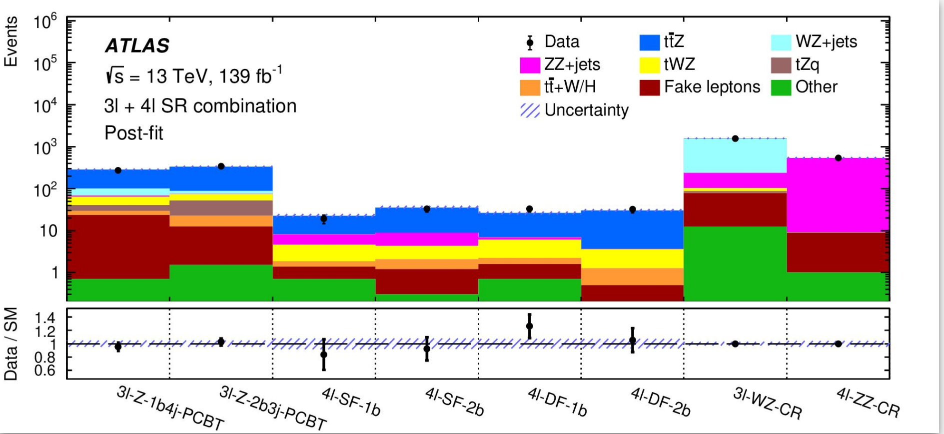
σ(ttZ) = 0.95 ± 0.05(stat) ± 0.06(syst) pb



LHCTopWG

tt+Z cross section measurement (ATLAS)

- Measurement of **ttZ in multilepton channels**
- Fit in lepton / jet / b-jet bins
- Backgrounds:
  - Non-prompt → data-driven
  - WZ/ZZ → CRs on Z peaks in 3/4ℓ
  - Remaining (e.g. t(t)+X) estimated from MC
- Observed: **σ(ttZ) = 0.99 ± 0.05(stat) ± 0.08(syst) pb**
  - Precision of 10%
  - Dominated by PS modeling, backgrounds, b-tagging
- Agreement with NLO+NNLL calculation *(EPJC 79 (2019) 249)*
  $\sigma(ttZ) = 0.86\ ^{+0.07}/_{-0.08}(\text{scale}) \pm 0.03\ (\text{pdf}+\alpha_S)$ pb

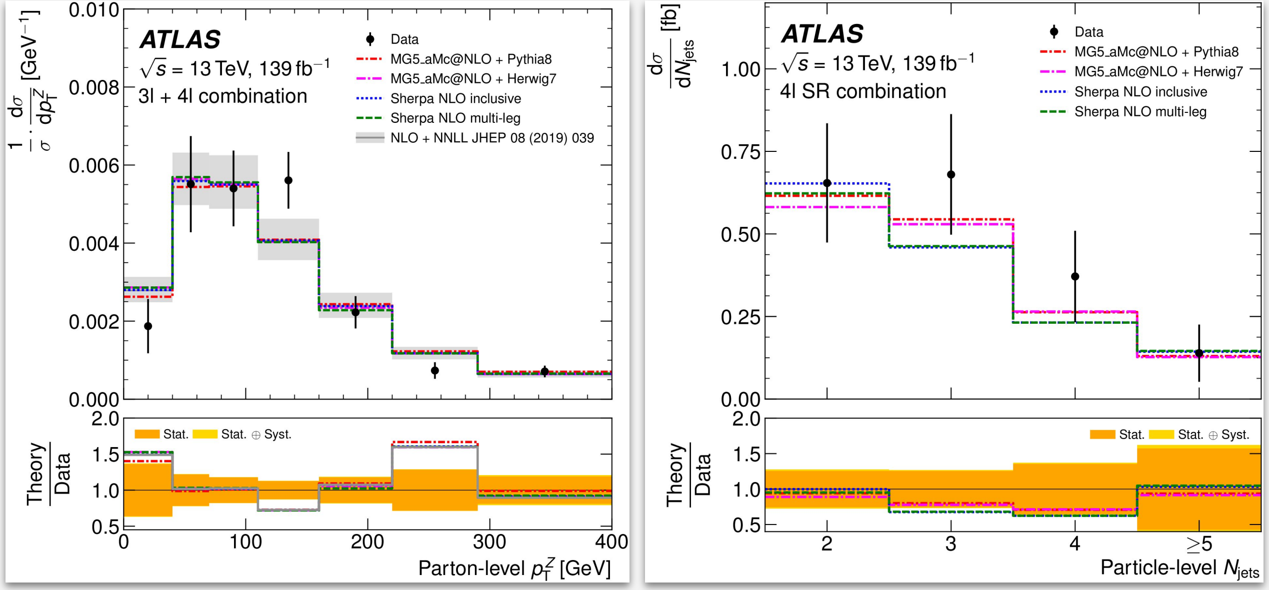


Channel	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\ ^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\ ^{+0.11}_{-0.10}\,(\text{syst.})$
Combination ($3\ell + 4\ell$)	$1.19 \pm 0.06\,(\text{stat.}) \pm 0.10\,(\text{syst.})$

ATLAS ttZ 3ℓ/4ℓ: EPCJ 81 (2021) 737

tt+Z cross section measurement (ATLAS)

- Differential measurement via unfolding to particle and parton level with RooUnfold
- Various observables in 3ℓ and 4ℓ channel
  - Probing tZ coupling, modeling of Z boson, top quark and additional radiation
- Compared to multiple simulations and NLO+NNLL calculation (JHEP 08, 039 (2019))
  - Similar trends for most simulations and calculations

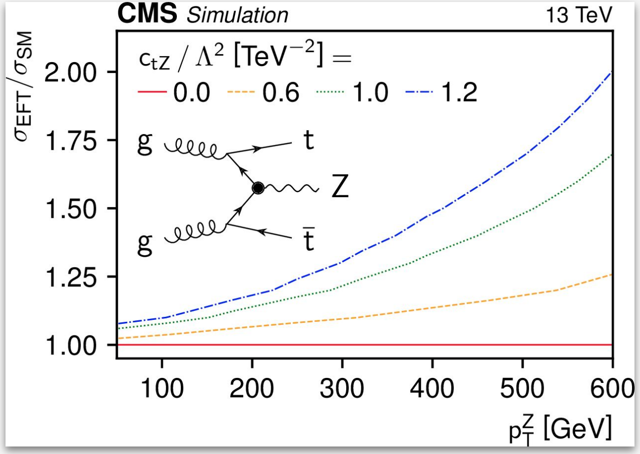


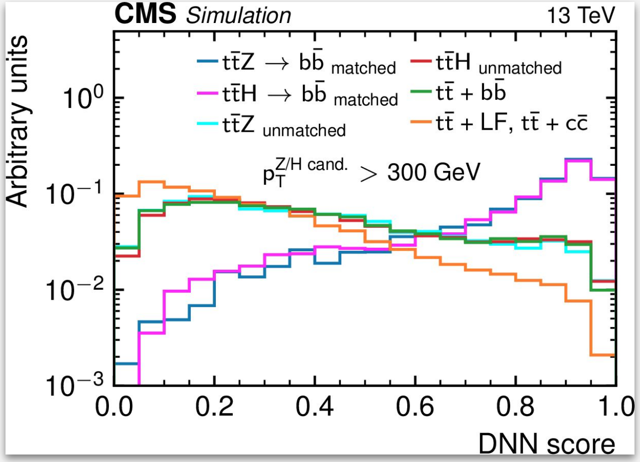
ATLAS ttZ 3ℓ/4ℓ: EPCJ 81 (2021) 737

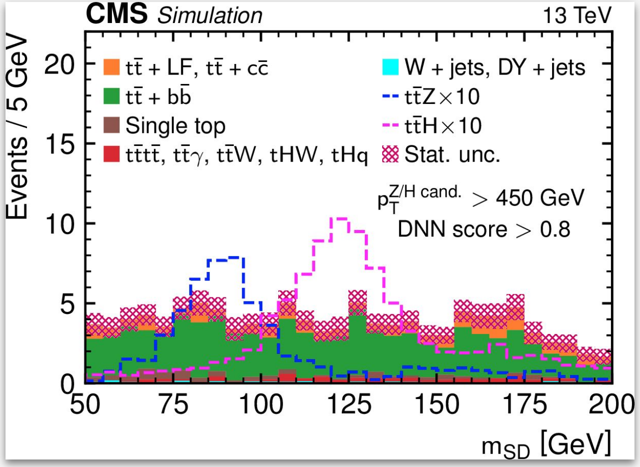
Also covered in EFT talk by Jon Wilson (Tuesday)

Boosted tt+Z/H cross section measurement (CMS)

- Measurement of **ttZ and ttH in boosted regime**
  - Single lepton channel, Xbb final state
  - Sensitive to anomalous couplings in boosted regime
- Tag AK8 jets as Z/Hbb resonance
- DNN to separate signals from backgrounds
  - Fit performed in AK8 soft-drop mass and DNN bins
- Backgrounds dominated by tt+jets / tt+bb
  - from simulation







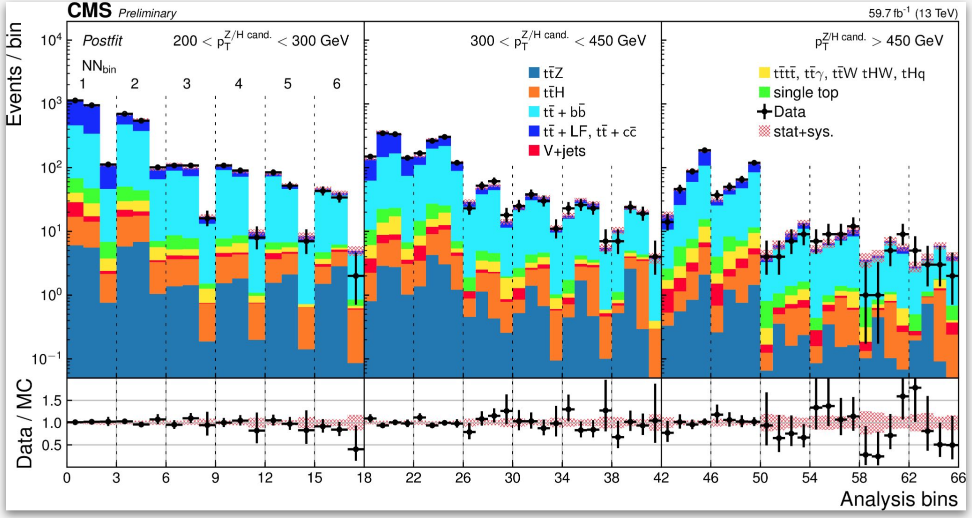
CMS boosted ttZ/H: *CMS-TOP-21-003* (submitted to PRD)

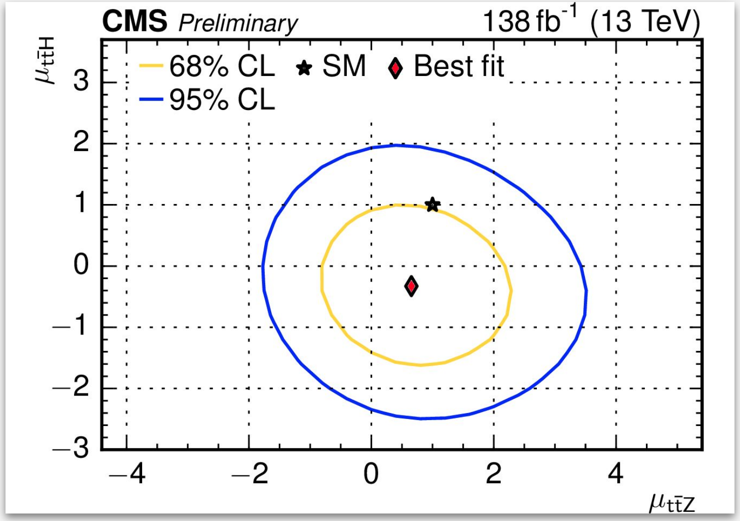
Also covered in EFT talk by Jon Wilson (Tuesday)

Boosted tt+Z/H cross section measurement (CMS)

- 2D measurement of ttZ and ttH → Results compatible with prediction
  - ➢ Low correlation (-10%) due to good separation of signals (soft-drop mass, DNN)
  - ➢ Sensitivity limited by data statistics, tt+heavy flavor modeling and b/bb-tagging

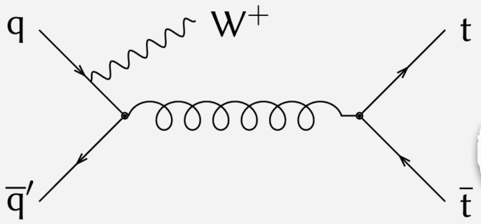
Signal strength	Observed	Stat.	MC stat.	Exp. syst.	Theo. syst.	Expected
$\mu_{t\bar{t}Z}$	$0.65\,^{+1.04}_{-0.98}$	$^{+0.80}_{-0.75}$	$^{+0.36}_{-0.38}$	$^{+0.38}_{-0.31}$	$^{+0.43}_{-0.38}$	$1.00\,^{+0.91}_{-0.84}$
$\mu_{t\bar{t}H}$	$-0.27\,^{+0.86}_{-0.83}$	$^{+0.72}_{-0.65}$	$^{+0.31}_{-0.33}$	$^{+0.19}_{-0.19}$	$^{+0.28}_{-0.35}$	$1.00\,^{+0.79}_{-0.72}$



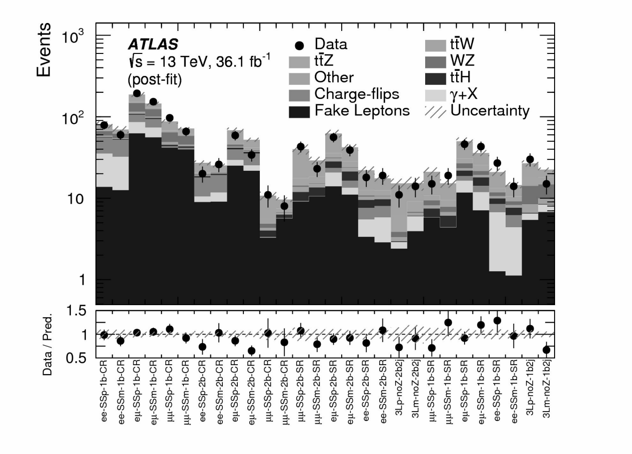


CMS boosted ttZ/H: *CMS-TOP-21-003* (submitted to PRD)

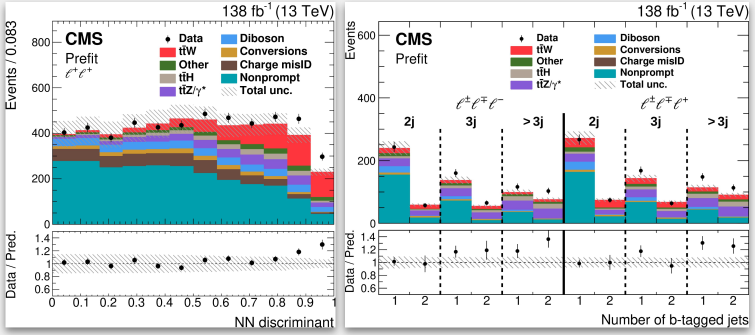
tt+W



36fb^{-1} ttW/ttZ 2ℓ/3ℓ/4ℓ: [PRD 99 (2019) 072009]

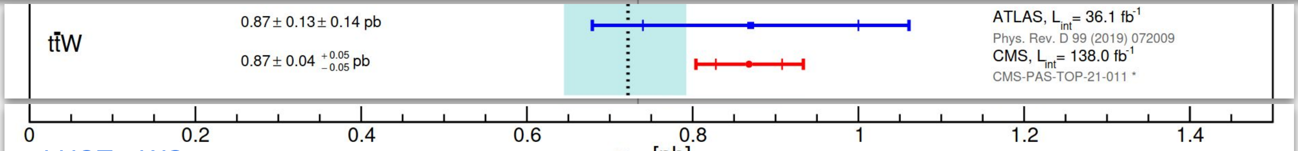


ttW 2ℓ/3ℓ: [CMS-TOP-21-011] (submitted to JHEP) 138fb^{-1}



σ(ttW) = 0.87 ± 0.13(stat) ± 0.14(syst) pb

σ(ttW) = 0.87 ± 0.04(stat) ± 0.05(syst) pb



[LHCTopWG]

Also covered in YSF talk by Tu Thong Tran (Tuesday)

tt+W cross section measurement (CMS)

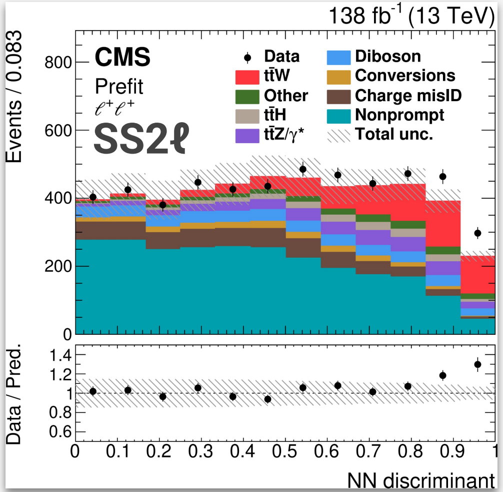
Dedicated Poster by Tu Thong Tran (Monday)

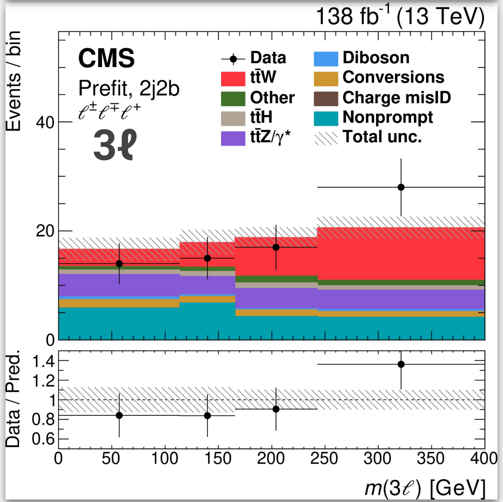
138fb^{-1}

- Measurement of **ttW in SS2ℓ/3ℓ regions**

- SS2ℓ region
  - ➢ DNN to separate non-prompt, ttZ, ttγ from ttW
  - ➢ Fit DNN scores separated by lepton flavors
- 3ℓ region
  - ➢ Separate events in jet / b-jet regions
  - ➢ Fit m_3(leptons) in each region (best S/B separation)

- Backgrounds:
  - ➢ Non-prompt leptons → data-driven estimation
  - ➢ Charge misidentification of electrons → from simulation
  - ➢ WZ/ZZ/ttZ → CR on Z peak





CMS ttW 2ℓ/3ℓ: CMS-TOP-21-011 (submitted to JHEP)

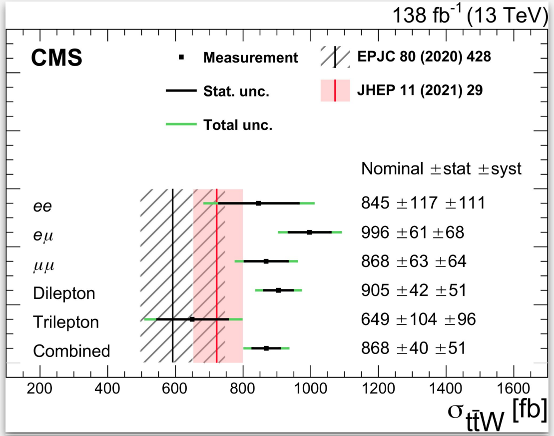
tt+W cross section measurement (CMS)

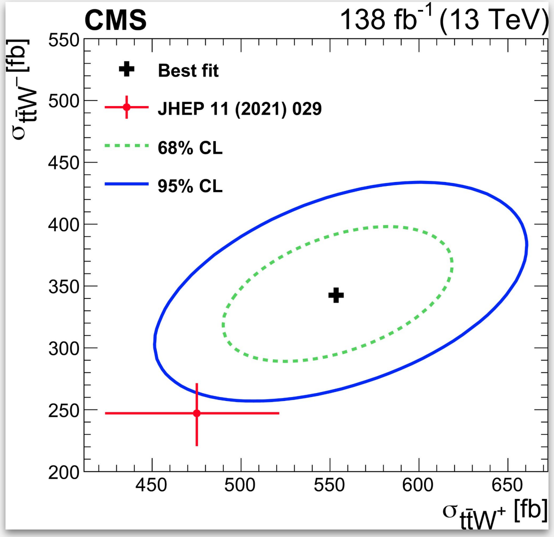
- Measurement of **ttW in 2ℓ/3ℓ regions**

- Observed: **σ(ttW) = 0.87 ± 0.04(stat) ± 0.05(syst) pb**
  - ➢ Precision of 10%
  - ➢ Dominated by ttH background, luminosity, charge misID, b-tagging

- Measurement shows trend to higher values than calculations:
  NLO+NNLL: **σ(ttW) = 0.59 $^{+0.16}/_{-0.10}$ pb** (EPCJ 80 (2020) 428)
  NLO+FxFx: **σ(ttW) = 0.72 $^{+0.07}/_{-0.08}$ pb** (JHEP 11 (2021) 29)

- Also measure ttW$^+$ and ttW$^-$ cross sections and ratio
  - ➢ Large difference expected due to qq initial state
  - ➢ **R(ttW$^+$/ttW$^-$) = 1.61 ± 0.15 (stat) $^{+0.07}/_{-0.05}$ (syst)**





CMS ttW 2ℓ/3ℓ: CMS-TOP-21-011 (submitted to JHEP)

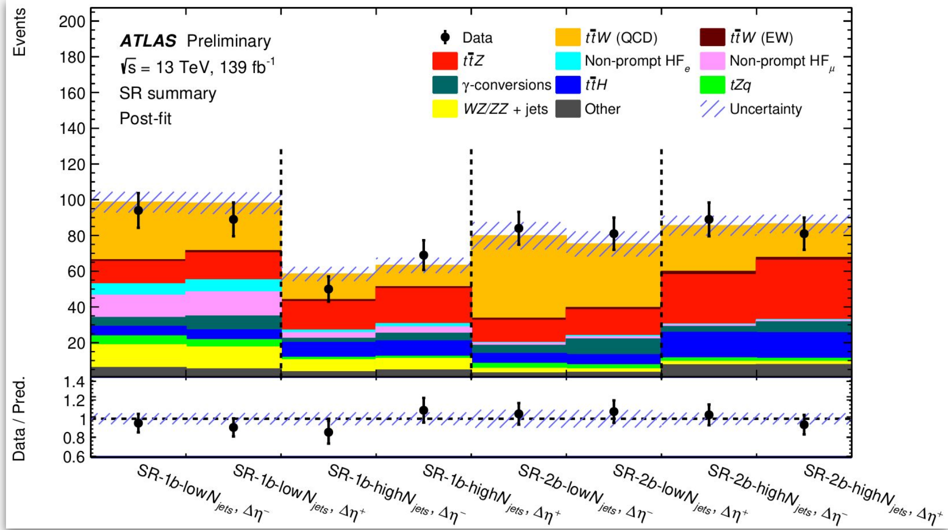
Also covered in YSF talk by Marcos Lopez (Tuesday) and Joker talk by James Keaveney (Thursday)

tt+W charge asymmetry (ATLAS)

NEW! 139fb^{-1}

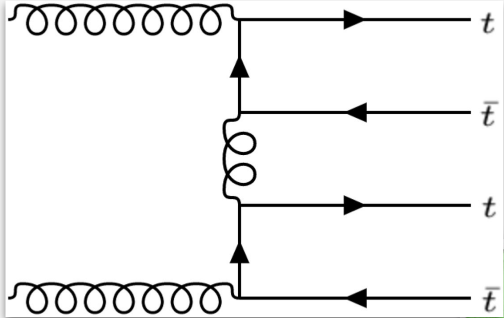
$$A_c^t = \frac{N(\Delta_y^t > 0) - N(\Delta_y^t < 0)}{N(\Delta_y^t > 0) + N(\Delta_y^t < 0)}$$

- Probe **charge asymmetry of top quarks and antiquarks**
  - ttW enhances qq initial state
  - Use charged leptons from top decays as proxy for top quarks
  - BDT for correct lepton identification
- Fit event yields in $\pm\Delta\eta^\ell$ regions
  - 3ℓ channel
- Fiducial result unfolded to particle-level:
  $A_C = -0.112 \pm 0.170$ (stat) ± 0.055 (syst)
  - Limited by signal and ttZ modeling and data statistics
- Compare to generator prediction (sherpa NLO QCD+EW):
  - **$A_C = -0.063\ ^{+0.007}/_{-0.004}$ (scale) ± 0.004 (MC stat)**
- Also confirms ttW norm. offset between simulation and data from other measurements

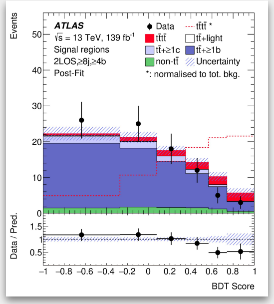


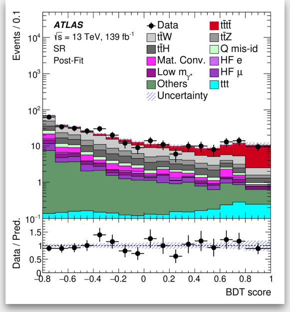
ATLAS ttW charge asymmetry: ATLAS-CONF-2022-062

tttt

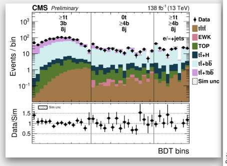


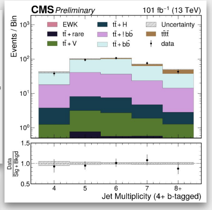
ATLAS EXPERIMENT	0ℓ	1ℓ	2ℓ (OS)	2ℓ (SS)	3ℓ+
2018		JHEP 11 (2021) 118		EPJC 80 (2020) 1085	
2017					
2016					

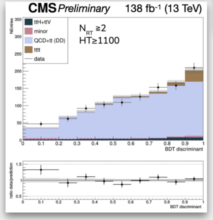


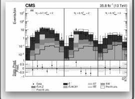


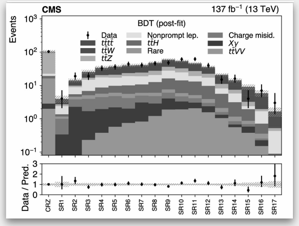
CMS	0ℓ	1ℓ	2ℓ (OS)	2ℓ (SS)	3ℓ+
2018	NEW! CMS-PAS-TOP-21-005			EPCJ 80 (2020) 75	
2017					
2016			JHEP 11 (2019) 082		





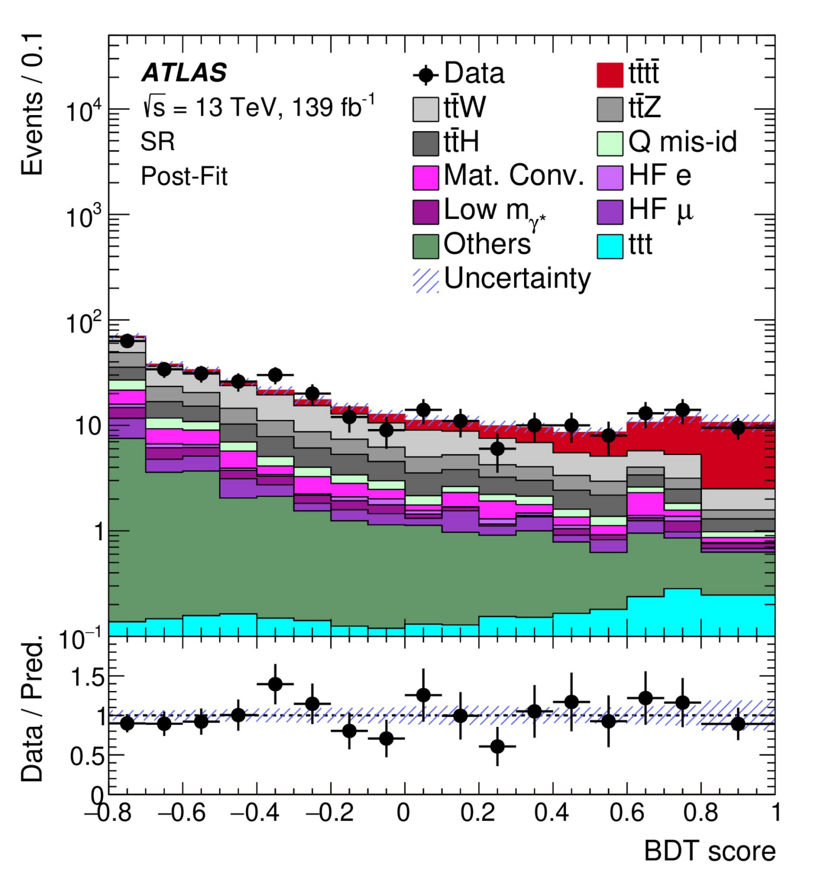






Status of four top searches (ATLAS)

- **Multi-lepton + SS2ℓ channel**
- Fit of BDT output in combined region
- Backgrounds:
  - ➢ Non-prompt leptons → data-driven
  - ➢ ttW+jets → dedicated CR
  - ➢ Other ttX → estimated from simulation
- Measured signal-strength:
  μ(tttt) = 2.0 ± 0.4(stat) $^{+0.7}/_{-0.4}$(syst) (4.3σ)
  - ➢ Limited by data statistics, signal and ttW modeling
  - ➢ Evidence for four top from this channel alone!



ATLAS four top SS2ℓ/3ℓ+: EPJC 80 (2020) 1085

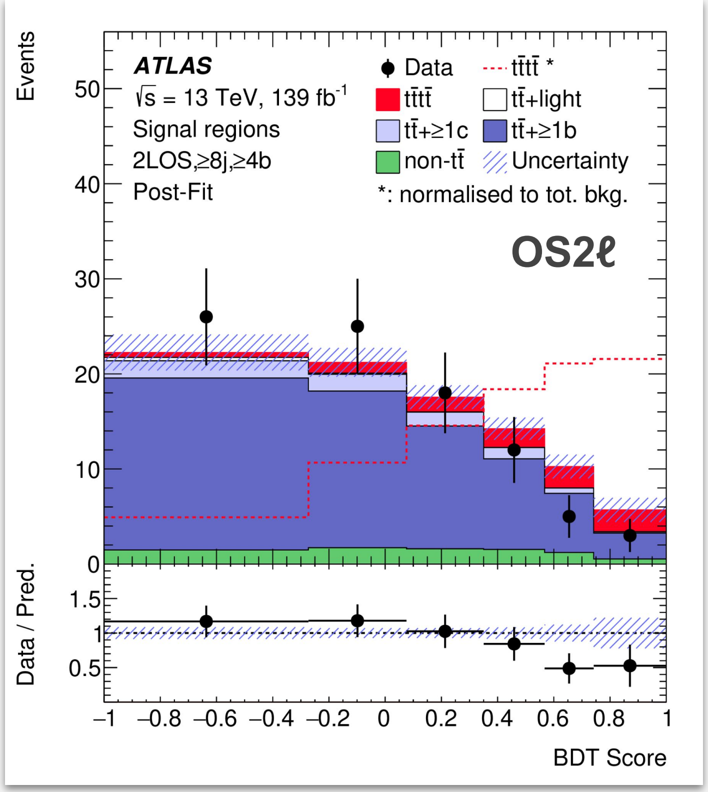
Status of four top searches (ATLAS)

- **1ℓ + OS2ℓ channel**

- Separated into jet / b-jet SRs and CRs
  - ➢ Fit of BDT output distribution in SRs and H_T in CRs
  - ➢ Also using AK10 jet features as BDT input

- Background mostly tt+jets
  - ➢ Estimation/reweighting from low b-jet CRs
  - ➢ Bad modeling at high b-jet regions

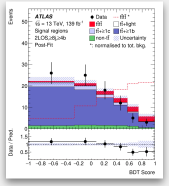
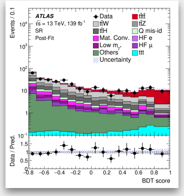
- Measured signal-strength:
  μ(tttt) = 2.2 ± 0.7(stat) $^{+1.5}/_{-1.0}$(syst) (1.9σ)
  - ➢ Dominated by signal and tt+b/c modeling and jets



ATLAS four top 1ℓ/OS2ℓ+: [JHEP 11 (2021) 118]

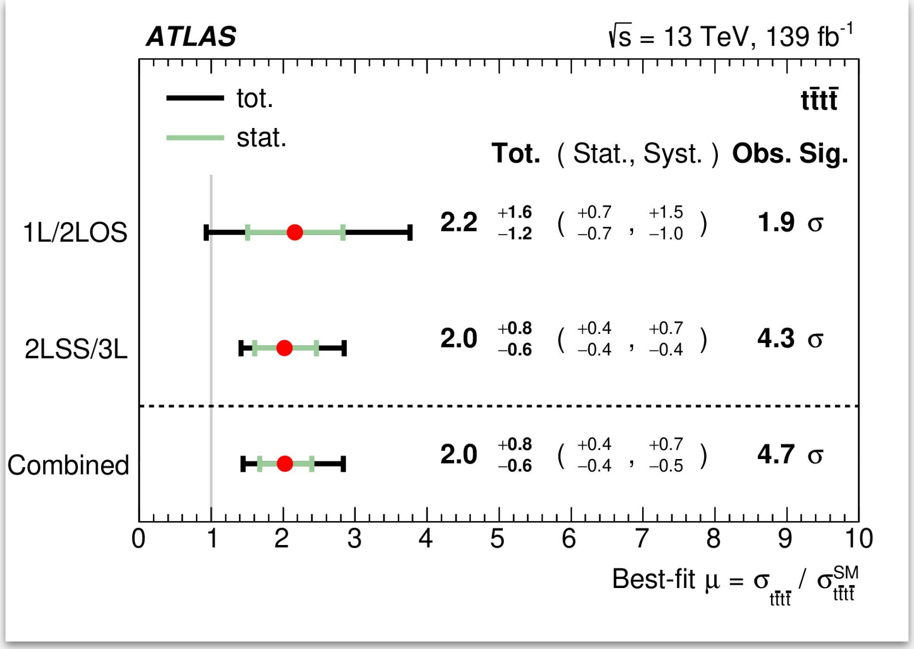
Status of four top searches (ATLAS)

- **Combination of ATLAS four top searches**
  - SS2ℓ/3ℓ+: *EPJC 80 (2020) 1085*
  - 1ℓ/OS2ℓ: *JHEP 11 (2021) 118*

	0ℓ	1ℓ	2ℓ (OS)	2ℓ (SS)	3ℓ+
2018		*JHEP 11 (2021) 118* 		*EPJC 80 (2020) 1085* 	
2017					
2016					

- Measured cross-section
  $\sigma(tttt)$ = 24 $^{+7}/_{-6}$ fb (4.7σ)

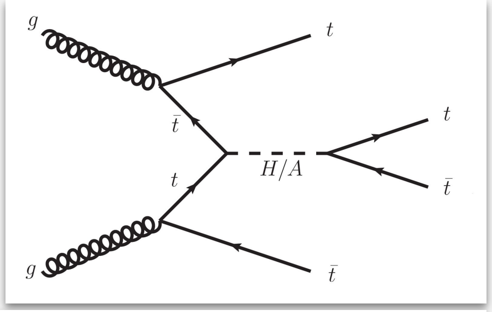
- Larger than NLO QCD+EW calculation (*JHEP 02 (2018) 031*)
  $\sigma(tttt)$ = 12.0 $^{+2.2}/_{-2.5}$ fb
  - Compatible within 2σ

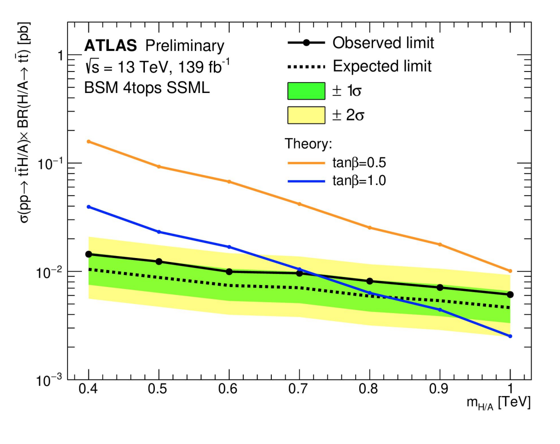


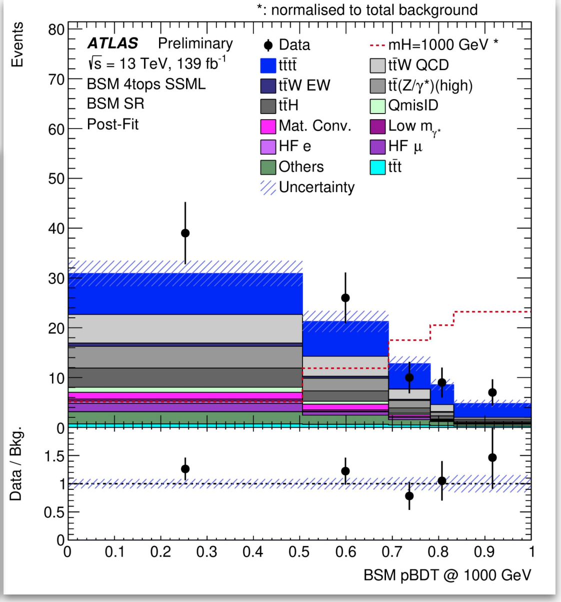
Also covered in BSM talk by Daniel Scheirich (Wednesday)

BSM four top search (ATLAS)

- **Search for ttH/A → tttt**
  - ➢ New heavy scalar H/A boson in H/A → tt decay
  - ➢ SS2ℓ final state (follows analysis strategy in *EPJC 80 (2020) 1085*)
- Baseline: Same BDT for four top identification
  - ➢ SR defined based on BDT output
- Additional mass-parameterized BDT for BSM identification
- **Limits on BSM signal**
  - ➢ m(H/A) range [400−1000] GeV
  - ➢ No excesses observed







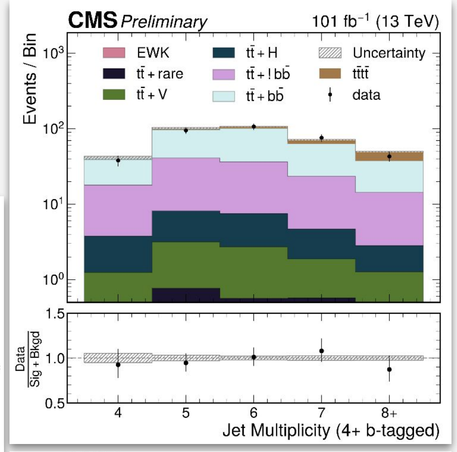
ATLAS ttH/A → tttt: *ATLAS-CONF-2022-008*

Also covered in JOKER talk by Nick Manganelli (Thursday)

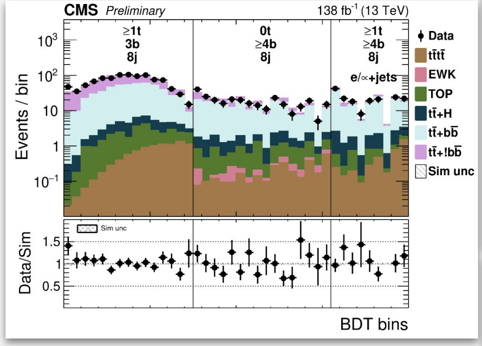
Status of four top searches (CMS)

NEW! $138 fb^{-1}$

- **OS2ℓ channel**
  - Fit H_T(jets) distributions in lepton / jet / b-jet categories
  - Low jet/b-jet categories function as CRs

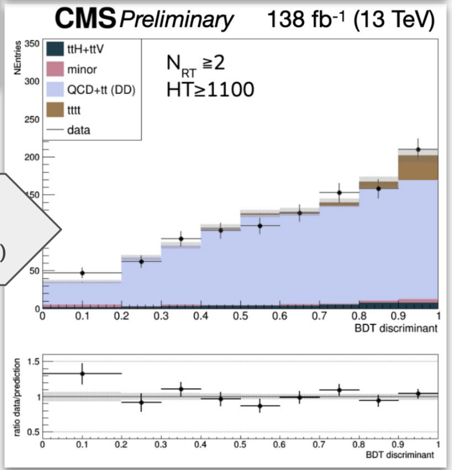


- **1ℓ channel**
  - BDT for signal / background separation
  - Resolved top tagger as BDT input
  - Lepton / jet / b-jet / top candidate regions



- **All-hadronic channel**
  - First time the all-hadronic channel is used in four top searches!
  - Fit output of BDT for signal / multijet separation
  - Categories of resolved / boosted top candidates and H_T
  - Data-driven estimation of multijet / tt+jets backgrounds

Dedicated Poster by Melissa Quinnan (Monday)



- Backgrounds: tt+jets / tt+bb (+ multijet in all-hadronic channel)

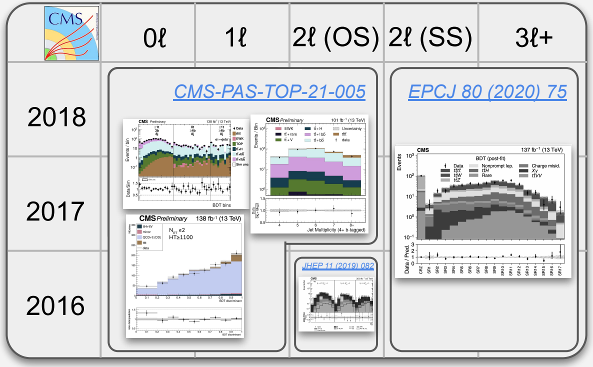
CMS four top 0ℓ/1ℓ/OS2ℓ: *CMS-PAS-TOP-21-005*

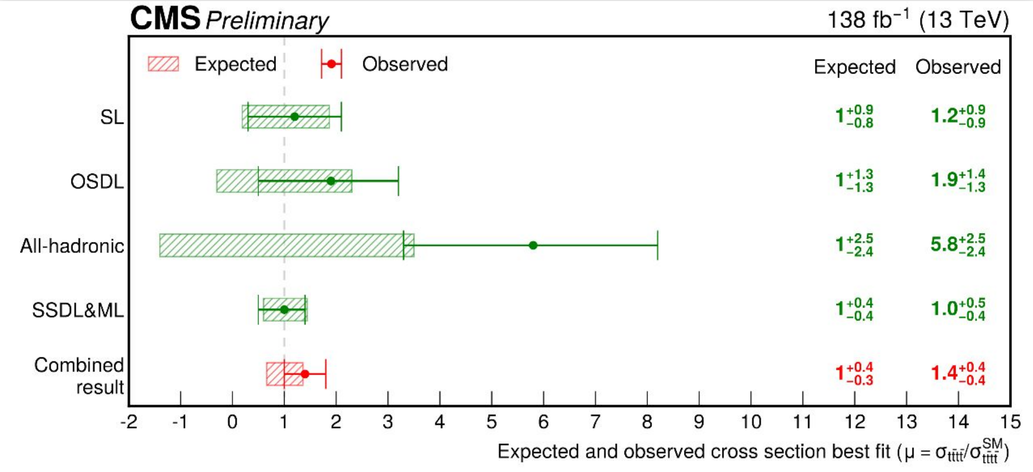
Also covered in JOKER talk by Nick Manganelli (Thursday)

Status of four top searches (CMS)

NEW! 138fb^{-1}

- **Combination of CMS four top searches**
  - ➢ NEW! 0ℓ/1ℓ/OS2ℓ: *CMS-PAS-TOP-21-005*
  - ➢ SS2ℓ/3ℓ+: *EPCJ 80 (2020) 75*
  - ➢ OS2ℓ (2016): *JHEP 11 (2019) 082*





- Combined signal-strength and significance:
  μ(tttt) = 1.4 ± 0.4 (4.0σ)
  - ➢ Limited by data statistics and ttbb background modeling

Analysis	Signal strength exp	Signal strength obs	Significance exp	Significance obs
OSDL	$1^{+1.4}_{-1.3}$	$1.6^{+1.4}_{-1.3}$	0.79	1.27
Single lepton	$1^{+0.87}_{-0.81}$	$1.2^{+0.9}_{-0.9}$	1.24	1.43
All-hadronic	$1^{+2.5}_{-2.4}$	$5.8^{+2.5}_{-2.4}$	0.42	2.46
New results only	$1^{+0.70}_{-0.66}$	$2.5^{+0.7}_{-0.7}$	1.52	3.88
SSDL & multilepton	$1^{+0.45}_{-0.40}$	$1.1^{+0.5}_{-0.4}$	2.70	2.56
All CMS 2016–2018	$1^{+0.36}_{-0.34}$	$1.4^{+0.4}_{-0.4}$	3.21	4.01

- Compatible with NLO QCD+EW calculation (*JHEP 02 (2018) 031*)
  σ(tttt) = 12.0 $^{+2.2}/_{-2.5}$ fb

Summary

- High precision **inclusive/differential measurements of tt+γ/Z/W**
  - Inclusive cross-sections established at 5–10% level
  - Many differential measurements
    - Important input for modeling of processes
    - Interpretations in EFT/BSM scenarios
  - Also: Collaboration of CMS+ATLAS on modeling of tt+W process (HiggsXSWG)

- Searches for **four top production**
  - Well-established evidence by ATLAS & CMS
  - Analyzed full RunII in almost all top decay channels
  - Observation by the individual experiments within reach

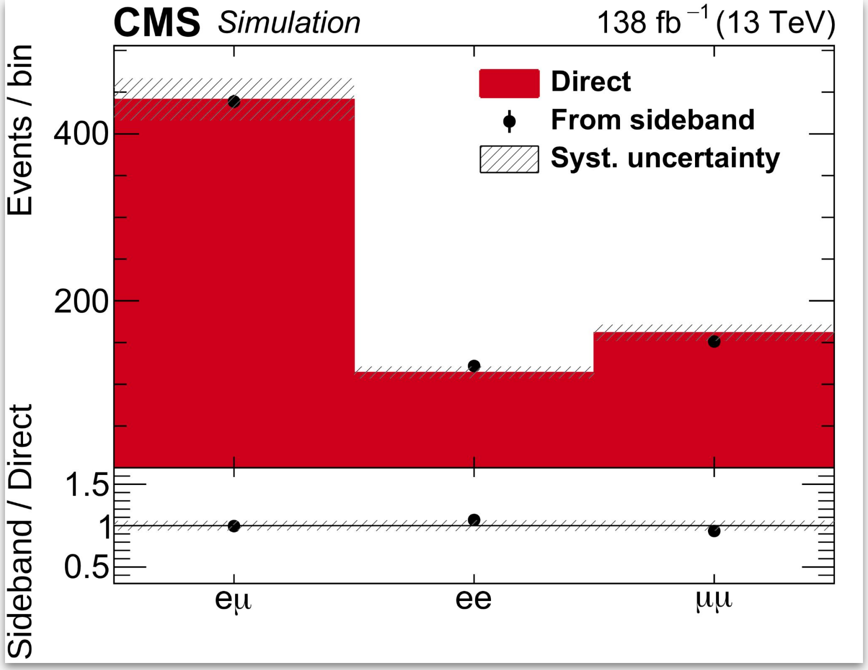
[Public ATLAS TOP Results](#)
[Public CMS TOP Results](#)
[LHCTopWG Summary Plots](#)

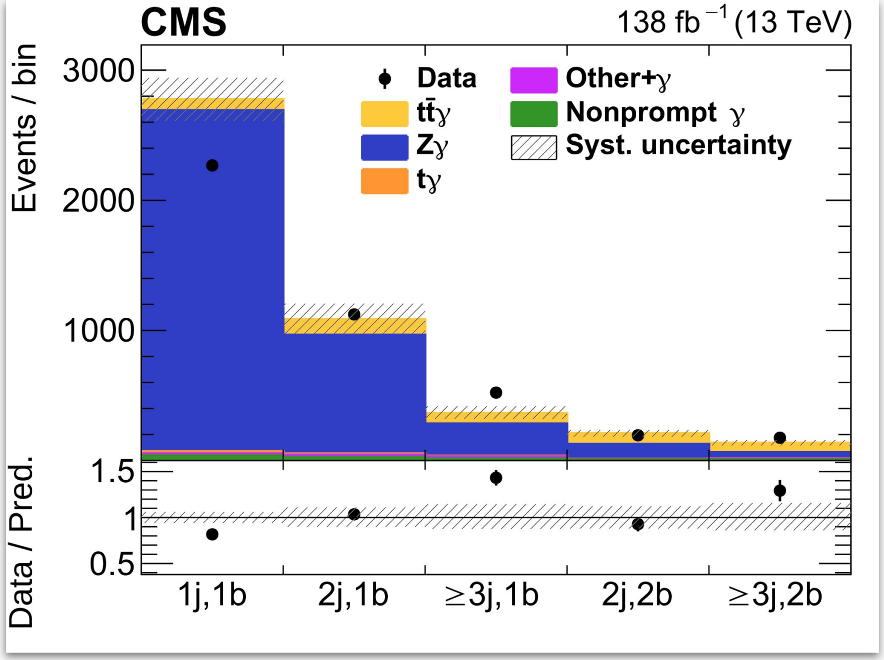
Backup

Also covered in EFT talk by Jon Wilson (Tuesday)

tt+γ cross section measurement (CMS)

❑ Measurement of **ttγ in OS2ℓ channel**





CMS ttγ 2ℓ: *JHEP 05 (2022) 091*

tt+γ cross section measurement (CMS)

138fb^{-1}

❑ Measurement of ttγ in OS2ℓ channel

Leptons	Photons	Jets	b jets	Events
$p_T > 25\,(15)$ GeV	$p_T > 20$ GeV	$p_T > 30$ GeV	$p_T > 30$ GeV	$N_\ell = 2$ (OC)
$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 1.44$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$N_\gamma = 1$
	$\Delta R(\gamma,\ell) > 0.4$	$\Delta R(\text{jet},\ell) > 0.4$	$\Delta R(\text{jet},\ell) > 0.4$	$N_b \geq 1$
	isolated	$\Delta R(\text{jet},\gamma) > 0.1$	$\Delta R(\text{jet},\gamma) > 0.1$	$m(\ell\ell) > 20$ GeV
			matched to b hadron	

Symbol	Definition
$p_T(\gamma)$	Transverse momentum of the photon
$\lvert\eta\rvert(\gamma)$	Absolute value of the pseudorapidity of the photon
$\min \Delta R(\gamma,\ell)$	Angular separation between the photon and the closest lepton
$\Delta R(\gamma,\ell_1)$	Angular separation between the photon and the leading lepton
$\Delta R(\gamma,\ell_2)$	Angular separation between the photon and the subleading lepton
$\min \Delta R(\gamma,b)$	Angular separation between the photon and the closest b jet
$\lvert\Delta\eta(\ell\ell)\rvert$	Pseudorapidity difference between the two leptons
$\Delta\varphi(\ell\ell)$	Azimuthal angle difference between the two leptons
$p_T(\ell\ell)$	Transverse momentum of the dilepton system
$p_T(\ell_1) + p_T(\ell_2)$	Scalar sum of the transverse momenta of the two leptons
$\min \Delta R(\ell,j)$	Smallest angular separation between any of the selected leptons and jets
$p_T(j_1)$	Transverse momentum of the leading jet

	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 simulated samples	×	1.5–7.6	0.9
	Total systematic uncertainty			3.6
	Statistical uncertainty			1.4
	Total uncertainty			3.9

CMS ttγ 2ℓ: JHEP 05 (2022) 091

Also covered in ML talk by Philip Keicher (Friday)

Charge asymmetry in tt+γ (ATLAS)

Dedicated Poster by Amartya Rej (Monday)

NEW! $139 fb^{-1}$

- Probe **charge asymmetry of top quarks and antiquarks**

	$O_{\mathrm{NN}} < 0.6$	$O_{\mathrm{NN}} \geq 0.6$
$t\bar{t}\gamma$ prod (signal)	6660 ± 350	6910 ± 340
$t\bar{t}\gamma$ decay	14100 ± 3100	1900 ± 560
h-fake γ	3400 ± 1400	790 ± 360
e-fake γ	6420 ± 860	1480 ± 260
prompt γ	6400 ± 2000	1300 ± 400
lepton fake	410 ± 110	57 ± 35
Total	$37\,400 \pm 4500$	$12\,400 \pm 1100$
Data	38527	13763

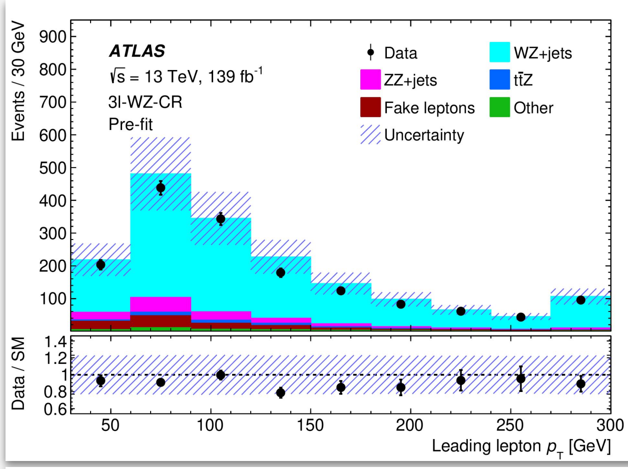
Total uncertainty	0.030
Statistical uncertainty	0.024
MC statistical uncertainties	
$t\bar{t}\gamma$ production	0.004
Background processes	0.008
Modelling uncertainties	
$t\bar{t}\gamma$ production modelling	0.003
Background modelling	0.002
Prompt background normalisation	0.003
Experimental uncertainties	
Jet and b-tagging	0.010
Fake lepton background estimate	0.005
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.009
Fake photon background estimates	0.004
Photon	0.003
Other experimental	0.004

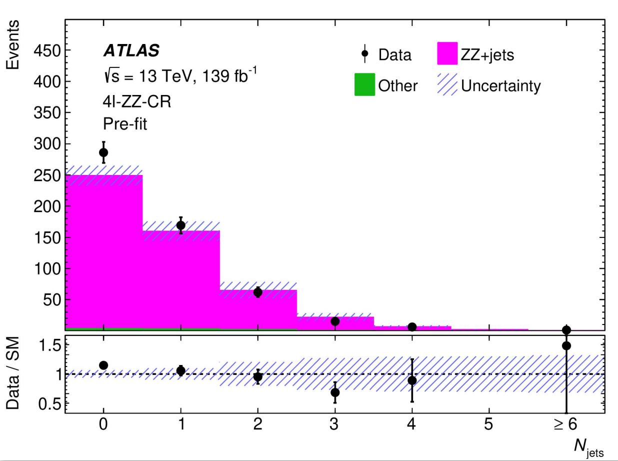
ATLAS ttγ charge asymmetry: ATLAS-CONF-2022-049

tt+Z cross section measurement (ATLAS)

- Measurement of **ttZ in multilepton channels**

Variable	3ℓ-WZ-CR	4ℓ-ZZ-CR
N_ℓ ($\ell = e, \mu$)	$= 3$	$= 4$
	1 OSSF lepton pair with	2 OSSF lepton pairs with
	$\lvert m_{\ell\ell} - m_Z\rvert < 10\,\mathrm{GeV}$	$\lvert m_{\ell\ell} - m_Z\rvert < 10\,\mathrm{GeV}$
$p_\mathrm{T}(\ell_1, \ell_2, \ell_3, \ell_4)$	$> 27, 20, 20\,\mathrm{GeV}$	$> 27, 20, 10, 7\,\mathrm{GeV}$
N_jets	≥ 3	–
$N_{b\text{-jets}}$@85%	$= 0$	–
$E_\mathrm{T}^\mathrm{miss}$	–	$20\,\mathrm{GeV} < E_\mathrm{T}^\mathrm{miss} < 40\,\mathrm{GeV}$





ATLAS ttZ 3ℓ/4ℓ: [EPCJ 81 (2021) 737]

tt+Z cross section measurement (ATLAS)

- Measurement of **ttZ in multilepton channels**

Variable	3ℓ-Z-$1b4j$-PCBT inclusive	3ℓ-Z-$2b3j$-PCBT inclusive	3ℓ-Z-$2b3j$ differential
N_ℓ ($\ell = e, \mu$)	= 3		
	$\geq$1 OSSF lepton pair with $\lvert m^Z_{\ell\ell} - m_Z\rvert < 10$ GeV		
	for all OSSF combinations: $m_{\mathrm{OSSF}} > 10$ GeV		
p_T (ℓ_1, ℓ_2, ℓ_3)	> 27, 20, 20 GeV		
N_{jets}	≥ 4	≥ 3	≥ 3
$N_{b\text{-jets}}$	= 1@60%	$\geq$ 2@70%	$\geq$ 2@85%
	veto add. b-jets@70%		

Variable	4ℓ-SF-$1b$	4ℓ-SF-$2b$	4ℓ-DF-$1b$	4ℓ-DF-$2b$
N_ℓ($\ell = e, \mu$)	= 4			
	$\geq$1 OSSF lepton pair with $\lvert m^Z_{\ell\ell} - m_Z\rvert < 10$ GeV			
	for all OSSF combinations: $m_{\mathrm{OSSF}} > 10$ GeV			
p_T (ℓ_1, ℓ_2, ℓ_3, ℓ_4)	> 27, 20, 10, 7 GeV			
$\ell\ell^{\text{non-}Z}$	e^+e^- or $\mu^+\mu^-$	e^+e^- or $\mu^+\mu^-$	$e^\pm\mu^\mp$	$e^\pm\mu^\mp$
$E_\mathrm{T}^{\mathrm{miss}}$	> 100 GeV, if $\lvert m^{\text{non-}Z}_{\ell\ell} - m_Z\rvert \leq 10$ GeV	> 50 GeV, if $\lvert m^{\text{non-}Z}_{\ell\ell} - m_Z\rvert \leq 10$ GeV	–	–
	> 50 GeV, if $\lvert m^{\text{non-}Z}_{\ell\ell} - m_Z\rvert > 10$ GeV	–		
N_{jets}	≥ 2	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$@85%	= 1	≥ 2	= 1	≥ 2

Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
WZ/ZZ + jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + $E_\mathrm{T}^{\mathrm{miss}}$	2.1
Fake leptons	2.1
$t\bar{t}Z$ ISR	1.6
$t\bar{t}Z$ μ_f and μ_r scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematic	8.4
Data statistics	5.2
Total	10

ATLAS ttZ 3ℓ/4ℓ: [EPCJ 81 (2021) 737]

tt+Z cross section measurement (ATLAS)

- Measurement of **ttZ in multilepton channels**

Region	3ℓ-Z-$1b4j$ -PCBT	3ℓ-Z-$2b3j$ -PCBT	4ℓ-SF-$1b$	4ℓ-SF-$2b$	4ℓ-DF-$1b$	4ℓ-DF-$2b$	3ℓ-WZ-CR	4ℓ-ZZ-CR
$t\bar{t}Z$	185 ± 16	247 ± 20	14.5 ± 1.7	26.9 ± 2.5	19.3 ± 1.8	26.7 ± 2.3	45 ± 11	0.8 ± 0.1
$WZ+l$	2.4 ± 1.8	0.2 ± 0.3	–	–	–	–	1068 ± 110	–
$WZ+b$	20 ± 11	10.8 ± 6.1	–	–	–	–	11.2 ± 6.3	–
$WZ+c$	10.8 ± 4.8	1.8 ± 0.8	–	–	–	–	207 ± 87	–
$ZZ+l$	0.3 ± 0.2	0.02 ± 0.02	1.7 ± 0.7	0.9 ± 0.5	0.5 ± 0.1	0.02 ± 0.01	121 ± 15	496 ± 26
$ZZ+b$	3.0 ± 1.6	2.0 ± 1.0	0.9 ± 0.6	2.5 ± 1.5	0.2 ± 0.1	0.07 ± 0.07	1.8 ± 0.9	12.9 ± 7.1
$ZZ+c$	0.7 ± 0.2	0.1 ± 0.1	0.9 ± 0.5	1.1 ± 0.6	0.2 ± 0.1	0.02 ± 0.01	13.0 ± 4.1	19.8 ± 7.1
tWZ	23.8 ± 4.0	20.5 ± 7.0	2.7 ± 0.4	2.2 ± 0.8	3.8 ± 1.1	2.3 ± 0.9	13.2 ± 1.2	0.2 ± 0.1
tZq	10.8 ± 4.5	29.7 ± 9.0	–	–	–	–	8.6 ± 3.2	–
$t\bar{t}+W/H$	5.8 ± 0.9	10.1 ± 2.2	0.5 ± 0.1	0.9 ± 0.1	0.6 ± 0.1	0.8 ± 0.1	1.8 ± 0.4	0.01 ± 0.01
Fake leptons	23 ± 11	11.0 ± 5.3	0.7 ± 0.3	0.9 ± 0.4	0.9 ± 0.5	0.3 ± 0.1	65 ± 31	7.9 ± 3.1
Other	0.7 ± 0.4	1.5 ± 0.7	0.7 ± 0.3	0.2 ± 0.1	0.7 ± 0.4	0.2 ± 0.1	12.4 ± 6.3	1.0 ± 0.5
SM total	286 ± 13	334 ± 15	22.5 ± 1.8	35.6 ± 2.7	26.1 ± 1.9	30.3 ± 2.2	1569 ± 43	539 ± 23
Data	272	343	19	33	33	32	1569	539

ATLAS ttZ 3ℓ/4ℓ: EPCJ 81 (2021) 737

tt+Z cross section measurement (ATLAS)

- Measurement of **ttZ in multilepton channels**

	Variable	Definition
$3\ell + 4\ell$	p_{T}^{Z}	Transverse momentum of the Z boson
	$\lvert y^{Z}\rvert$	Absolute value of the rapidity of the Z boson
3ℓ	N_{jets}	Number of selected jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
	$p_{\mathrm{T}}^{\ell,\text{non-}Z}$	Transverse momentum of the lepton which is not associated with the Z boson
	$\lvert\Delta\phi(Z, t_{\mathrm{lep}})\rvert$	Azimuthal separation between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay
	$\lvert\Delta y(Z, t_{\mathrm{lep}})\rvert$	Absolute rapidity difference between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay
4ℓ	N_{jets}	Number of selected jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
	$\lvert\Delta\phi(\ell_t^{+}, \ell_{\bar{t}}^{-})\rvert$	Azimuthal separation between the two leptons from the $t\bar{t}$ system
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$	Azimuthal separation between the Z boson and the $t\bar{t}$ system
	$p_{\mathrm{T}}^{t\bar{t}}$	Transverse momentum of the $t\bar{t}$ system

ATLAS ttZ 3ℓ/4ℓ: [EPCJ 81 (2021) 737]

Also covered in EFT talk by Jon Wilson (Tuesday)

Boosted tt+Z/H cross section measurement (CMS)

138fb^{-1}

❑ Measurement of **ttZ and ttH in boosted regime**

Missing transverse momentum	$p_{\mathrm{T}}^{\mathrm{miss}} > 20\,\mathrm{GeV}$
=1 electron or muon	$p_{\mathrm{T}}(\mathrm{e}) > 30$ (35 GeV) in 2016 (2017 and 2018) $p_{\mathrm{T}}(\mu) > 30\,\mathrm{GeV}$ $\lvert\eta(\mathrm{e})\rvert < 2.5$, $\lvert\eta(\mu)\rvert < 2.4$ $I_{\mathrm{mini}}(\mathrm{e})/p_{\mathrm{T}}(\mathrm{e}) < 0.2$, $I_{\mathrm{mini}}(\mu)/p_{\mathrm{T}}(\mu) < 0.1$
≥1 AK8 jet	$p_{\mathrm{T}} > 200\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$ $50 < m_{\mathrm{SD}} < 200\,\mathrm{GeV}$
=1 Z or Higgs boson candidate AK8 jet	Highest $\mathrm{b\bar{b}}$ tagger score (>0.8)
≥5 AK4 jets (may overlap AK8 jets)	$p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$
≥2 b-tagged AK4 jets	Satisfy medium DEEPCSV b tag requirements ΔR(b-tagged AK4 jet, Z or Higgs boson candidate) > 0.8

Source of uncertainty	$\Delta\mu_{\mathrm{t\bar{t}Z}}$	$\Delta\mu_{\mathrm{t\bar{t}H}}$
$\mathrm{t\bar{t}} + \mathrm{c\bar{c}}$ cross section	$^{+0.27}_{-0.23}$	$^{+0.14}_{-0.13}$
$\mathrm{t\bar{t}} + \mathrm{b\bar{b}}$ cross section	$^{+0.18}_{-0.24}$	$^{+0.16}_{-0.22}$
$\mathrm{t\bar{t}} + 2\mathrm{b}$ cross section	$^{+0.03}_{-0.03}$	± 0.09
μ_{R} and μ_{F} scales	$^{+0.12}_{-0.14}$	$^{+0.11}_{-0.15}$
Parton shower	$^{+0.16}_{-0.17}$	$^{+0.07}_{-0.06}$
b tagging efficiency	$^{+0.25}_{-0.13}$	± 0.10
$\mathrm{b\bar{b}}$ tagging efficiency	$^{+0.18}_{-0.13}$	$^{+0.07}_{-0.04}$
Jet energy scale and resolution	± 0.11	$^{+0.11}_{-0.12}$
Jet mass scale and resolution	± 0.10	± 0.08

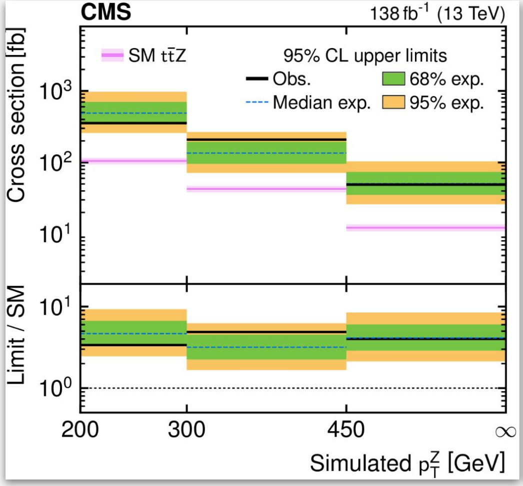
Name	Description
$\mathrm{t\bar{t}}$ system	
b p_{T}	p_{T} of the leading (subleading) b jet
b score	DEEPCSV score of the leading (subleading) b jet
q p_{T}	p_{T} of the leading (subleading) non-b jet
q score	DEEPCSV score of the leading (subleading) non-b jet
$\Delta R(\mathrm{b},\mathrm{q})$	minimum ΔR between the leading (subleading) b jet and any non-b jet
$\Delta R(\mathrm{q},\mathrm{q})$	ΔR between the non-b jets closest and next-to-closest to the leading (subleading) b jet
$m(\mathrm{q}+\mathrm{q})$	invariant mass of the non-b jets closest and next-to-closest to the leading (subleading) b jet
$\Delta R(\mathrm{b},\mathrm{q}+\mathrm{q})$	ΔR between the leading (subleading) b jet and the sum of the nearest and next-to-nearest non-b jets
$m(\mathrm{b}+\mathrm{q}+\mathrm{q})$	invariant mass of the leading (subleading) b jet and the nearest and next-to-nearest non-b jets
$\Delta R(\mathrm{Z/H},\mathrm{b}+\mathrm{q}+\mathrm{q})$	ΔR between the Z or Higgs boson candidate and the sum of the leading (subleading) b jet and the non-b jets nearest and next-to-nearest to the leading (subleading) b jet
$\Delta R(\mathrm{Z/H},\mathrm{b}+\mathrm{b}+\mathrm{q}+\mathrm{q}+\ell)$	ΔR between the Z or Higgs boson candidate and the sum of the leading and subleading b jets, the non-b jets nearest and next-to-nearest to the leading (subleading) b jet, and the lepton
$m_{\mathrm{T}}(\mathrm{b}+\ell,\vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	transverse mass of the subleading b jet and the lepton
$m(\mathrm{Z/H}+\mathrm{b})$	invariant mass of the Z or Higgs boson candidate and the nearest b jet
$m(\mathrm{b}+\mathrm{b})$	invariant mass of the leading and subleading b jets
$\Delta R(\mathrm{b},\mathrm{b})$	ΔR between the leading and subleading b jets
$\Delta R(\mathrm{Z/H},\mathrm{q})$	ΔR between the Z or Higgs boson candidate and the leading non-b jet
$\Delta R(\mathrm{Z/H},\mathrm{b})$	ΔR between the Z or Higgs boson candidate and the leading b jet
$\Delta R(\mathrm{Z/H},\ell)$	ΔR between the Z or Higgs boson candidate and the lepton
$m(\mathrm{Z/H}+\ell)$	invariant mass of the Z or Higgs boson candidate and the lepton
$\Delta R(\mathrm{b},\ell)$	ΔR between the leading (subleading) b jet and the lepton
$m(\mathrm{b}+\ell)$	invariant mass of the leading (subleading) b jet and the lepton
$N(\mathrm{b}_{\mathrm{out}})$	number of b jets outside the Z or Higgs boson candidate cone ($\Delta R > 0.8$)
$N(\mathrm{q}_{\mathrm{out}})$	number of non-b jets outside the Z or Higgs boson candidate cone ($\Delta R > 0.8$)
Event topology	
N(AK8 jets)	number of AK8 jets, including the Z or Higgs boson candidate
N(AK4 jets)	number of AK4 jets
$N(\mathrm{Z/H})$	number of AK8 jets with a minimum AK8 $\mathrm{b\bar{b}}$ tagger score of 0.8
AK8 m_{SD}	maximum m_{SD} of AK8 jets, excluding the Z or Higgs boson candidate
$H_{\mathrm{T}}(\mathrm{b}_{\mathrm{out}})$	H_{T} of the b jets outside the Z or Higgs boson candidate cone ($\Delta R > 0.8$)
$H_{\mathrm{T}}(\mathrm{b}_{\mathrm{out}},\mathrm{q}_{\mathrm{out}},\ell)$	H_{T} of all AK4 jets outside the Z or Higgs boson candidate cone ($\Delta R > 0.8$) and the lepton
sphericity	sphericity calculated from the AK4 jets and the lepton [?]
aplanarity	aplanarity calculated from the AK4 jets and the lepton [?]
Z or Higgs boson candidate substructure	
b_{in} score	maximum (minimum) DEEPCSV score of AK4 jets within the Z or Higgs boson candidate cone ($\Delta R < 0.8$)
$\Delta R(\mathrm{b}_{\mathrm{in}},\mathrm{b}_{\mathrm{out}})$	ΔR between one b jet within the Z or Higgs boson candidate cone ($\Delta R < 0.8$) and the leading b jet outside of the Z or Higgs boson candidate cone
$N(\mathrm{b}_{\mathrm{in}})$	number of b jets within the Z or Higgs boson candidate cone ($\Delta R < 0.8$)
$N(\mathrm{q}_{\mathrm{in}})$	number of non-b jets within the Z or Higgs boson candidate cone ($\Delta R < 0.8$)
Z/H $\mathrm{b\bar{b}}$ score	AK8 $\mathrm{b\bar{b}}$ tagger score of the Z or Higgs boson candidate

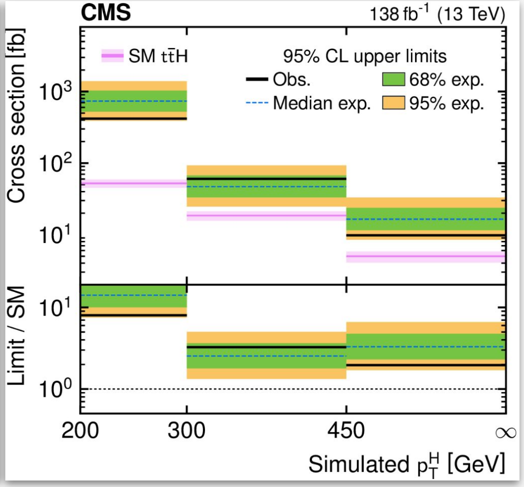
CMS boosted ttZ/H: *CMS-TOP-21-003* (submitted to PRD)

Also covered in [EFT talk](#) by Jon Wilson (Tuesday)

Boosted tt+Z/H cross section measurement (CMS)

- Measurement of **ttZ and ttH in boosted regime**





Signal	$p_T^{Z/H}$ interval [GeV]	95% CL upper limit [fb]		95% CL upper limit / SM	
		Observed	Expected	Observed	Expected
$t\bar{t}Z$	200–300	360	490^{+210}_{-140}	3.4	$4.7^{+2.0}_{-1.4}$
	300–450	209	135^{+58}_{-40}	4.9	$3.2^{+1.4}_{-0.9}$
	>450	49	51^{+23}_{-15}	4.0	$4.1^{+1.9}_{-1.3}$
$t\bar{t}H$	200–300	420	740^{+300}_{-210}	8.0	$14.1^{+5.7}_{-4.1}$
	300–450	60	47^{+20}_{-14}	3.2	$2.5^{+1.1}_{-0.8}$
	>450	9.8	$16.5^{+7.3}_{-4.9}$	2.0	$3.3^{+1.5}_{-1.0}$

CMS boosted ttZ/H: *[CMS-TOP-21-003](#)* (submitted to PRD)

Also covered in YSF talk by Tu Thong Tran (Tuesday)

tt+W cross section measurement (CMS)

Dedicated Poster by Tu Thong Tran (Monday)

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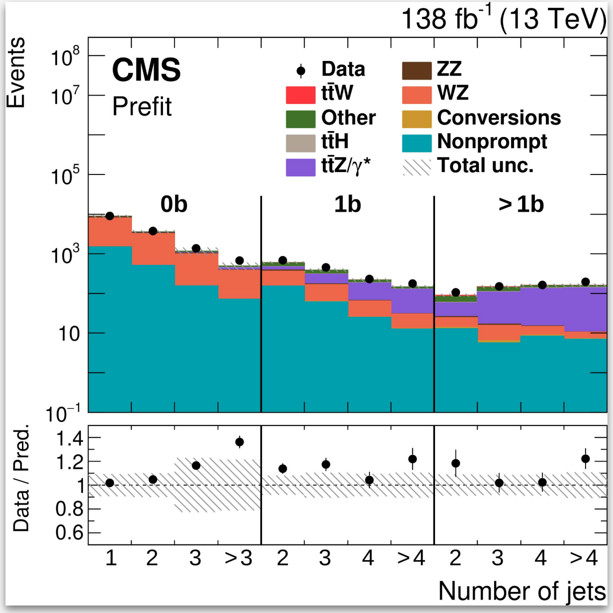
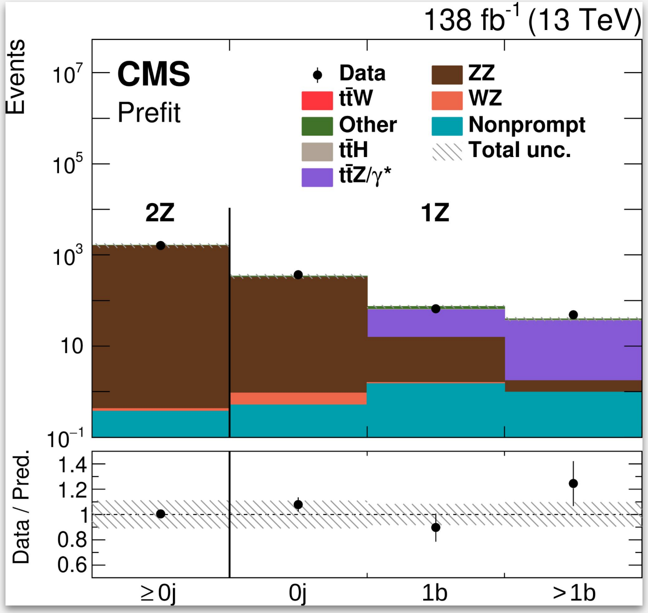
- Measurement of **ttW in SS2ℓ/3ℓ regions**





CMS ttW 2ℓ/3ℓ: *CMS-TOP-21-011* (submitted to JHEP)

Also covered in YSF talk by Tu Thong Tran (Tuesday)

tt+W cross section measurement (CMS)

Dedicated Poster by Tu Thong Tran (Monday)

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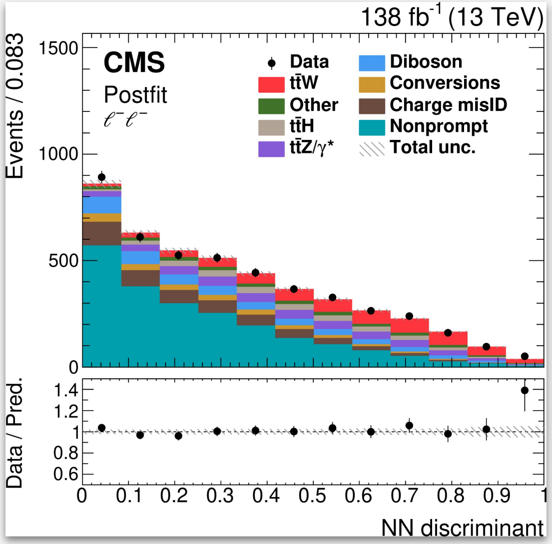
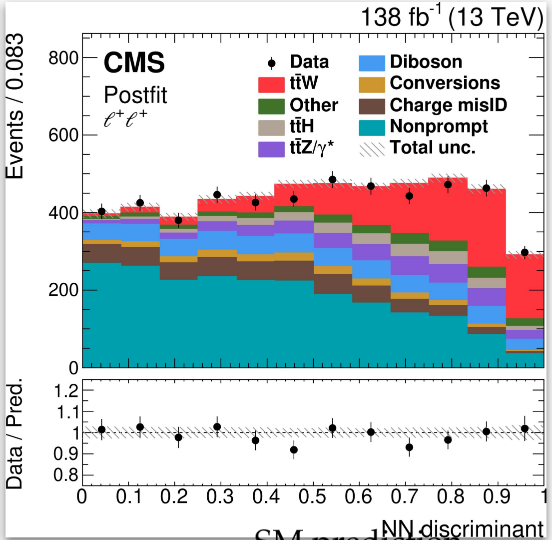
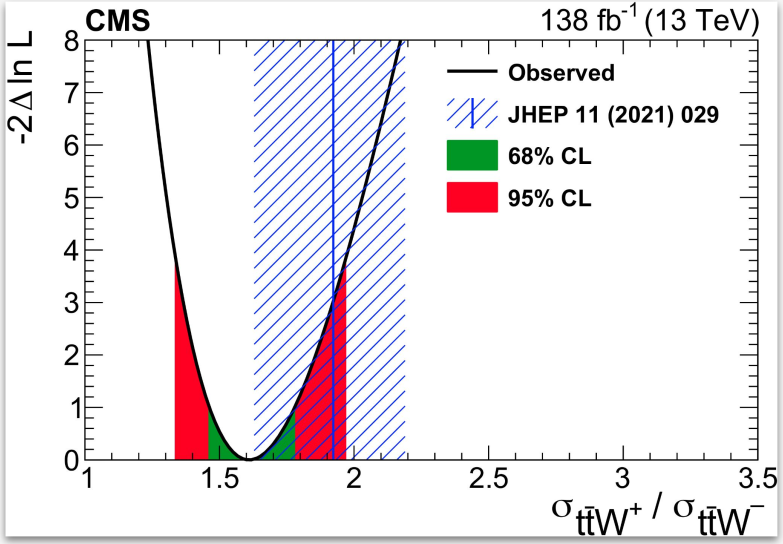
- Measurement of **ttW in SS2ℓ/3ℓ regions**







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

CMS ttW 2ℓ/3ℓ: *CMS-TOP-21-011* (submitted to JHEP)

Also covered in YSF talk by Tu Thong Tran (Tuesday)

tt+W cross section measurement (CMS)

Dedicated Poster by Tu Thong Tran (Monday)

138fb^{-1}

- Measurement of **ttW in SS2ℓ/3ℓ regions**

Process	$\ell^+\ell^+$	$\ell^-\ell^-$	$\ell^\pm\ell^\mp\ell^+$	$\ell^\pm\ell^\mp\ell^-$
$t\bar{t}W$	677 ± 21	355 ± 12	119.4 ± 9.2	65.3 ± 5.4
Nonprompt	2490 ± 600	2360 ± 570	325 ± 75	298 ± 71
Charge misID	520 ± 110	520 ± 111	—	—
$t\bar{t}H$	167 ± 34	169 ± 34	56 ± 12	57 ± 12
$t\bar{t}Z/\gamma^*$	335 ± 26	333 ± 26	145 ± 13	147 ± 13
Diboson	382 ± 88	285 ± 65	46.8 ± 9.1	38.0 ± 7.5
Other	178 ± 34	126 ± 27	43.4 ± 8.2	33.5 ± 7.4
Conversions	177 ± 54	192 ± 59	22.9 ± 7.1	24.0 ± 7.4
Total background	4250 ± 620	4000 ± 590	639 ± 80	600 ± 76
Total prediction	4920 ± 620	4350 ± 590	758 ± 81	663 ± 76
Data	5143	4486	834	744

Source	Uncertainty [%]
Experimental uncertainties	
Integrated luminosity	1.9
b tagging efficiency	1.6
Trigger efficiency	1.2
Pileup reweighting	1.0
L1 inefficiency	0.7
Jet energy scale	0.6
Jet energy resolution	0.4
Lepton selection efficiency	0.4
Background uncertainties	
$t\bar{t}H$ normalization	2.6
Charge misidentification	1.6
Nonprompt leptons	1.3
VVV normalization	1.2
$t\bar{t}VV$ normalization	1.2
Conversions normalization	0.7
$t\bar{t}\gamma$ normalization	0.6
ZZ normalization	0.6
Other normalizations	0.5
$t\bar{t}Z$ normalization	0.3
WZ normalization	0.2
tZq normalization	0.2
tHq normalization	0.2
Modeling uncertainties	
$t\bar{t}W$ scale	1.8
$t\bar{t}W$ color reconnection	1.0
ISR & FSR scale 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
Simulation statistical uncertainty	1.8
Total systematic uncertainty	5.8

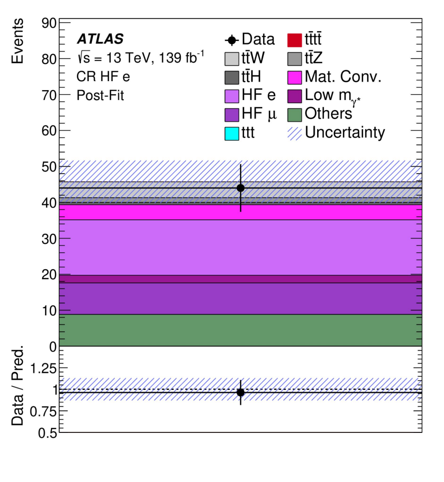
CMS ttW 2ℓ/3ℓ: *CMS-TOP-21-011* (submitted to JHEP)

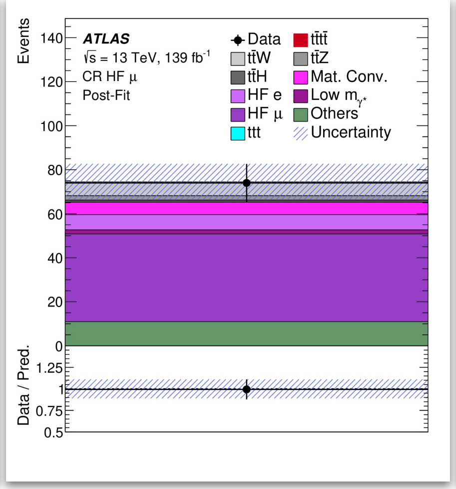
Status of four top searches (ATLAS)

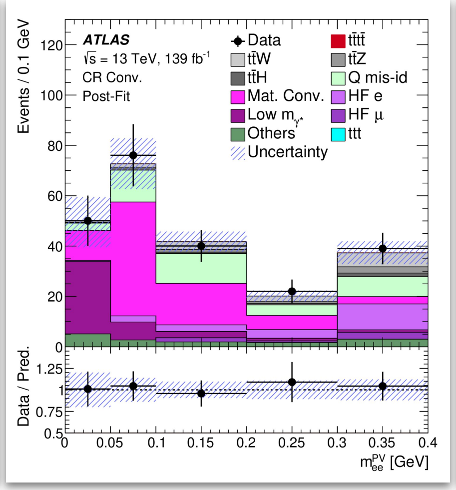
❑ Multi-lepton + SS2ℓ channel

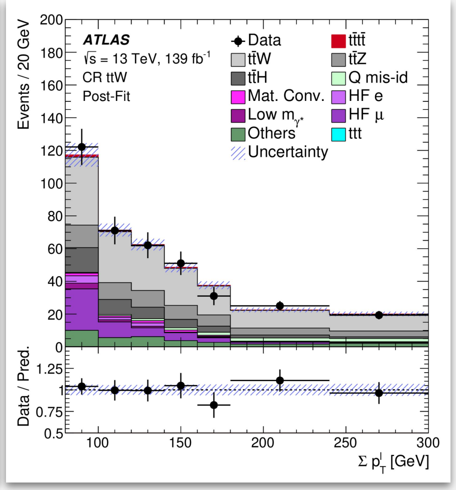
Region	Channel	N_j	N_b	Other requirements	Fitted variable
SR	2LSS/3L	≥ 6	≥ 2	$H_T > 500$	BDT
CR Conv.	$e^\pm e^\pm \| \| e^\pm \mu^\pm$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1\text{ GeV}]$ $200 < H_T < 500$ GeV	m_{ee}^{PV}
CR HF e	$eee \| \| ee\mu$	-	$= 1$	$100 < H_T < 250$ GeV	counting
CR HF μ	$e\mu\mu \| \| \mu\mu\mu$	-	$= 1$	$100 < H_T < 250$ GeV	counting
CR ttW	$e^\pm \mu^\pm \| \| \mu^\pm \mu^\pm$	≥ 4	≥ 2	$m_{ee}^{CV} \notin [0, 0.1\text{ GeV}]$, $\lvert\eta(e)\rvert < 1.5$ for $N_b = 2$, $H_T < 500$ GeV or $N_j < 6$ for $N_b \geq 3$, $H_T < 500$ GeV	Σp_T^ℓ

Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } m_{\gamma^*}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4









ATLAS four top SS2ℓ/3ℓ+: [EPJC 80 (2020) 1085]

Status of four top searches (ATLAS)

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Multi-lepton + SS2ℓ channel

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$+jets modelling	+0.26	−0.27
$t\bar{t}t$ modelling	+0.10	−0.07
Non-prompt leptons modelling	+0.05	−0.04
$t\bar{t}H$+jets modelling	+0.04	−0.01
$t\bar{t}Z$+jets modelling	+0.02	−0.04
Other background modelling	+0.03	−0.02
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-flavour jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Jet flavour tagging (c-jets)	+0.03	−0.01
Other experimental uncertainties	+0.03	−0.01
Total systematic uncertainty	+0.70	−0.44
Statistical	+0.42	−0.39
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.83	−0.60

	SR	SR and BDT > 0
$t\bar{t}W$+jets	102 ± 26	23 ± 10
$t\bar{t}WW$	7 ± 4	2 ± 1
$t\bar{t}Z$+jets	48 ± 9	9 ± 2
$t\bar{t}H$+jets	38 ± 9	8 ± 2
Q mis-id	16 ± 1	2.7 ± 0.2
Mat. Conv.	19 ± 6	3 ± 1
Low m_{γ^*}	9 ± 4	0.9 ± 0.5
HF e	3 ± 3	1 ± 1
HF μ	12 ± 6	3 ± 2
LF	4 ± 5	1 ± 1
Other fake	6 ± 2	2 ± 1
VV,VVV,VH	3 ± 2	0.2 ± 0.2
tZq, tWZ	5 ± 2	1.0 ± 0.4
Other $t\bar{t}X$	3 ± 2	1 ± 1
$t\bar{t}t$	3 ± 3	2 ± 2
Total bkg	278 ± 22	59 ± 10
$t\bar{t}t\bar{t}$	60 ± 17	44 ± 12
Total	337 ± 18	103 ± 10
Data	330	105

ATLAS four top SS2ℓ/3ℓ+: EPJC 80 (2020) 1085

BSM four top search (ATLAS)

❑ Search for ttH/A → tttt

Process	Pre-fit	Post-fit
$t\bar{t}t\bar{t}$	22.3 ± 5.4	25.9 ± 5.4
$t\bar{t}W$ QCD	9.4 ± 9.3	17.1 ± 6.9
$t\bar{t}W$ EW	1.3 ± 0.5	1.4 ± 0.6
$t\bar{t}WW$	1.8 ± 1.0	1.9 ± 1.0
$t\bar{t}(Z/\gamma^*)$ (high mass)	8.5 ± 2.2	9.2 ± 2.3
$t\bar{t}H$	7.2 ± 1.7	7.8 ± 1.7
QmisID	2.1 ± 0.1	2.1 ± 0.1
Mat. Conv.	1.8 ± 0.6	3.0 ± 1.2
Low m_{γ^*}	1.2 ± 0.6	0.8 ± 0.8
HF e	0.6 ± 0.5	0.6 ± 0.5
HF μ	2.7 ± 1.0	2.9 ± 1.2
LF	1.1 ± 1.2	0.4 ± 1.0
Other fake	1.1 ± 0.7	1.3 ± 0.7
tZ, tWZ	0.9 ± 0.3	0.9 ± 0.3
VV, VH, VVV	0.3 ± 0.1	0.3 ± 0.1
$t\bar{t}t$	1.9 ± 1.9	2.3 ± 2.1
$t\bar{t}WZ$, $t\bar{t}ZZ$, $t\bar{t}WH$, $t\bar{t}HH$	1.3 ± 0.3	1.4 ± 0.3
Total background	65.6 ± 13.2	79.5 ± 6.8
$t\bar{t}H(\to t\bar{t})$, $m_H = 400$ GeV	38.6 ± 2.4	–
$t\bar{t}H(\to t\bar{t})$, $m_H = 1000$ GeV	4.4 ± 0.2	–
Data	91	

Region	Channel	N_j	N_b	Other selection cuts	Fitted variable
CR Conv	$e^\pm e^\pm \,\|\|\, e^\pm \mu^\pm$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1]$ GeV $200 < H_T < 500$ GeV	m_{ee}^{PV}
CR HF e	$eee \,\|\|\, ee\mu$		$= 1$	$100 < H_T < 250$ GeV	Yield
CR HF μ	$e\mu\mu \,\|\|\, \mu\mu\mu$		$= 1$	$100 < H_T < 250$ GeV	Yield
CR $t\bar{t}W$	$e^\pm \mu^\pm \,\|\|\, \mu^\pm \mu^\pm$	≥ 4	≥ 2	$m_{ee}^{CV} \notin [0, 0.1]$ GeV, $\|\eta(e)\| < 1.5$ for $N_b = 2$, $H_T < 500$ GeV or $N_j < 6$; for $N_b \geq 3$, $H_T < 500$ GeV	$\sum p_T^\ell$
CR lowBDT	SS+3L	≥ 6	≥ 2	$H_T > 500$ GeV, SM BDT < 0.55	SM BDT
BSM SR	SS+3L	≥ 6	≥ 2	$H_T > 500$ GeV, SM BDT $\geq$ 0.55	BSM pBDT

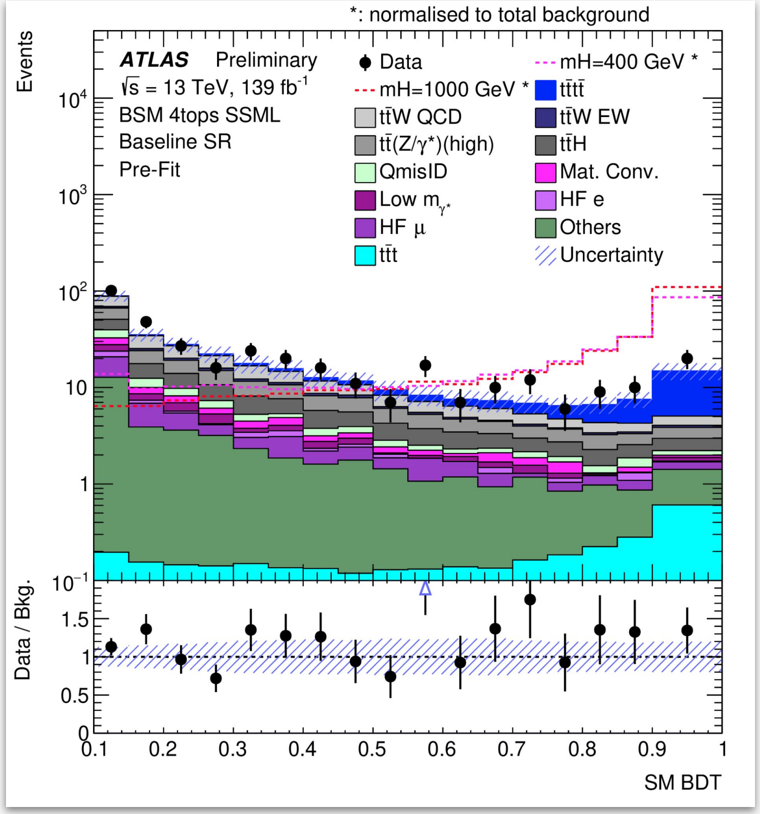
Parameter	$\lambda_{t\bar{t}W\,\mathrm{QCD}}$	$\lambda_{\mathrm{Mat.\,Conv.}}$	$\lambda_{\mathrm{Low}\,m_{\gamma^*}}$	$\lambda_{\mathrm{HF}\,e}$	$\lambda_{\mathrm{HF}\,\mu}$
Value	1.3 ± 0.3	1.5 ± 0.5	0.6 ± 0.5	0.9 ± 0.4	1.0 ± 0.2

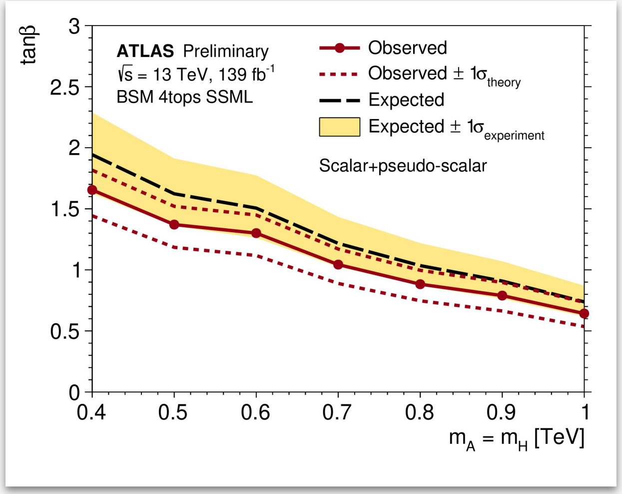
ATLAS ttH/A → tttt: ATLAS-CONF-2022-008

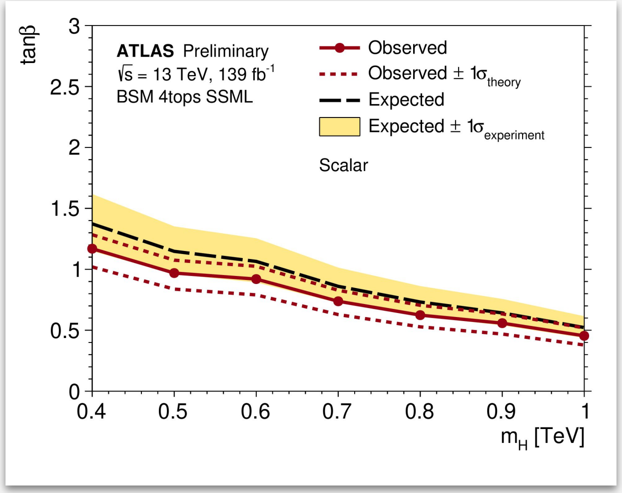
Also covered in BSM talk by Daniel Scheirich (Wednesday)

BSM four top search (ATLAS)

- Search for ttH/A → tttt







ATLAS ttH/A → tttt: ATLAS-CONF-2022-008

Status of four top searches (ATLAS)

❑ 1ℓ + OS2ℓ channel

Uncertainty source	Description	Components (number)
$t\bar{t}+\geq 1b$ normalisation	±50%	$t\bar{t}+b$, $t\bar{t}+b\bar{b}$, $t\bar{t}+B$, $t\bar{t}+\geq 3b$ (4)
$t\bar{t}+\geq 1c$ normalisation	±50%	$t\bar{t}+\geq 1c$ (1)
Generator choice	Powheg vs MadGraph5_aMC@NLO	($t\bar{t}$+light, $t\bar{t}+\geq 1c$, $t\bar{t}+b$, $t\bar{t}+b\bar{b}$, $t\bar{t}+B$, $t\bar{t}+\geq 3b$) $\otimes$ (shape, migration) (12)
PS choice	Pythia 8 vs Herwig 7	($t\bar{t}$+light, $t\bar{t}+\geq 1c$, $t\bar{t}+b$, $t\bar{t}+b\bar{b}$, $t\bar{t}+B$, $t\bar{t}+\geq 3b$) $\otimes$ (shape, migration) (12)
Renormalisation scale	Varying μ_r in Powheg	$t\bar{t}$+light, $t\bar{t}+\geq 1c$, $t\bar{t}+\geq 1b$ (3)
Factorisation scale	Varying μ_f in Powheg	$t\bar{t}$+light, $t\bar{t}+\geq 1c$, $t\bar{t}+\geq 1b$ (3)
ISR	Varying α_S^{ISR}(PS) in Pythia 8	$t\bar{t}$+light, $t\bar{t}+\geq 1c$, $t\bar{t}+\geq 1b$ (3)
FSR	Varying μ_f (PS) in Pythia 8	$t\bar{t}$+light, $t\bar{t}+\geq 1c$, $t\bar{t}+\geq 1b$ (3)
5FS vs 4FS	PowhegBoxRes (4FS) vs PowhegBox (5FS)	$t\bar{t}+b$, $t\bar{t}+b\bar{b}$, $t\bar{t}+B$, $t\bar{t}+\geq 3b$ (4)

ATLAS four top 1ℓ/OS2ℓ+: *JHEP 11 (2021) 118*

Status of four top searches (ATLAS)

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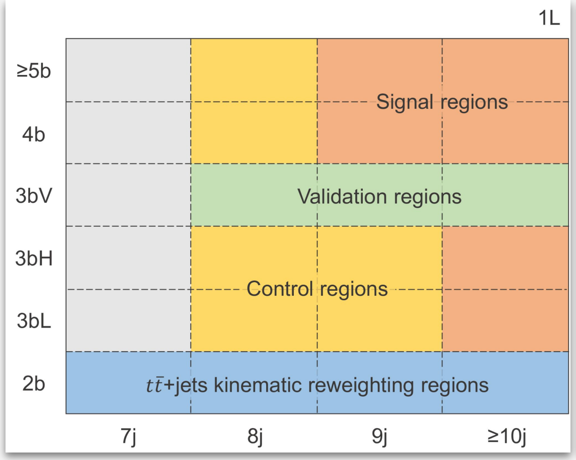
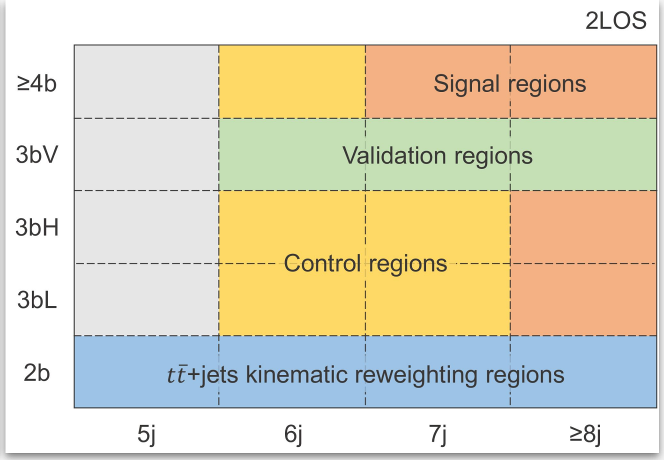
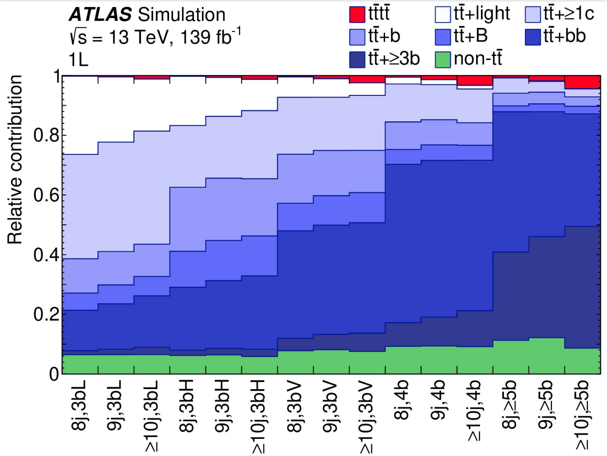
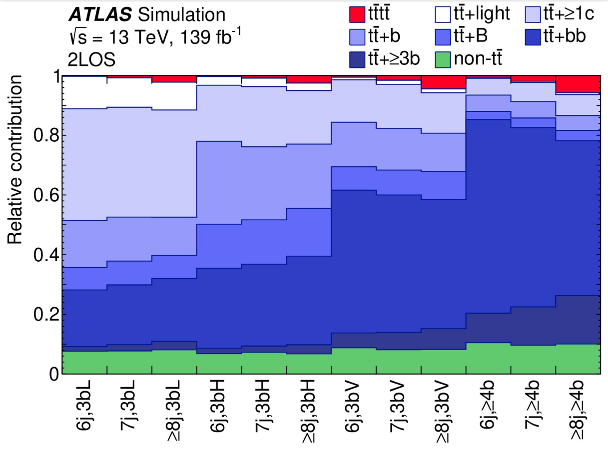
❑ 1ℓ + OS2ℓ channel

Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	= 2	-
3bL	≤ 2	= 3	-
3bH	= 3	= 3	= 3
3bV	= 3	= 3	≥ 4
≥4b (2LOS)	-	≥ 4	-
4b (1L)	-	= 4	-
≥5b (1L)	-	≥ 5	-





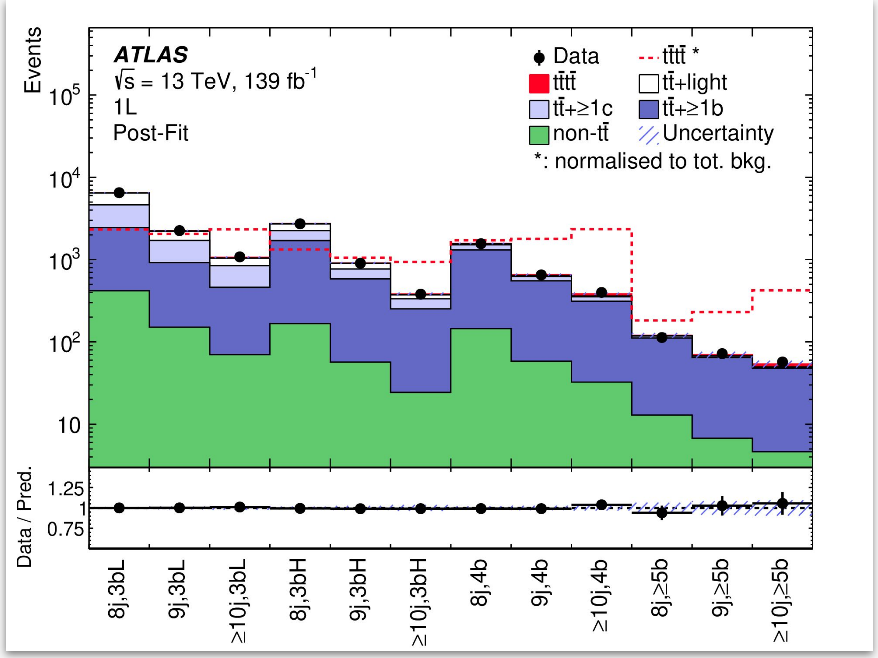


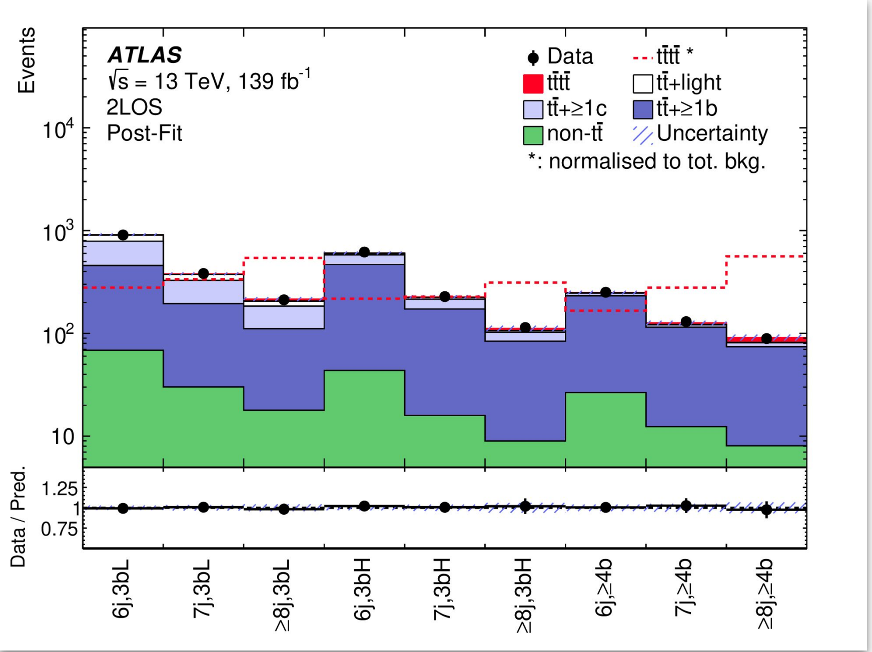


ATLAS four top 1ℓ/OS2ℓ+: [JHEP 11 (2021) 118]

Status of four top searches (ATLAS)

- 1ℓ + OS2ℓ channel

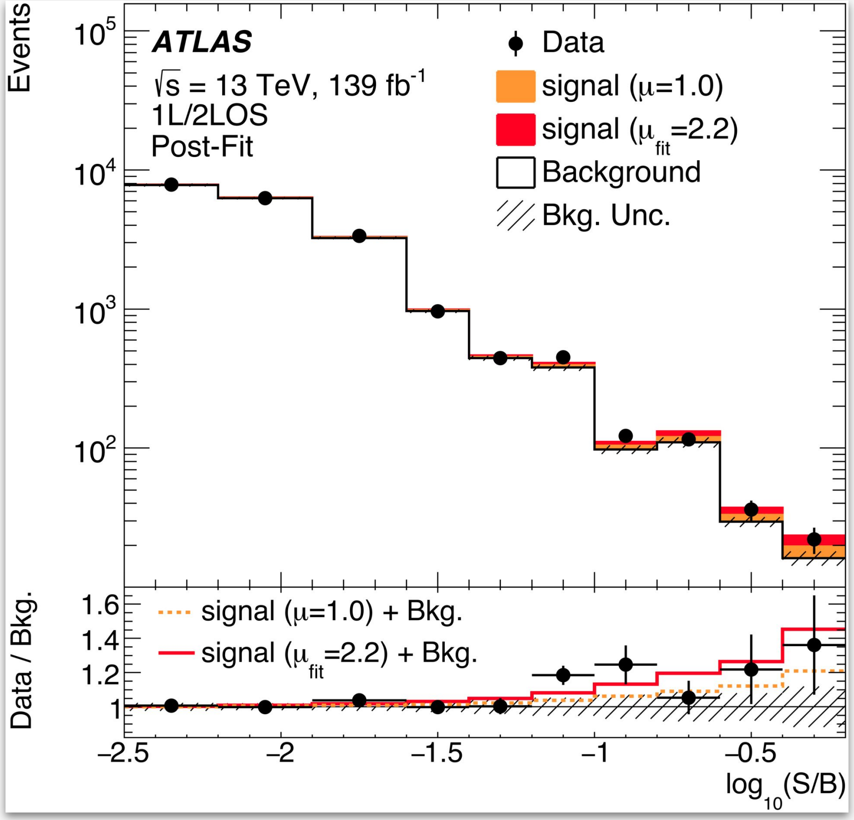




ATLAS four top 1ℓ/OS2ℓ+: JHEP 11 (2021) 118

Status of four top searches (ATLAS)

❑ 1ℓ + OS2ℓ channel



Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
Signal Modelling		
$t\bar{t}t\bar{t}$ modelling	+8	−3
Background Modelling		
$t\bar{t}+\geq 1b$ modelling	+8	−7
$t\bar{t}+\geq 1c$ modelling	+5	−4
$t\bar{t}$+jets reweighting	+4	−3
Other background modelling	+4	−3
$t\bar{t}$+light modelling	+2	−2
Experimental		
Jet energy scale and resolution	+6	−4
b-tagging efficiency and mis-tag rates	+4	−3
MC statistical uncertainties	+2	−2
Luminosity	< 1	
Other uncertainties	< 1	
Total systematic uncertainty	+15	−12
Statistical uncertainty	+8	−8
Total uncertainty	+17	−15

ATLAS four top 1ℓ/OS2ℓ+: [JHEP 11 (2021) 118]

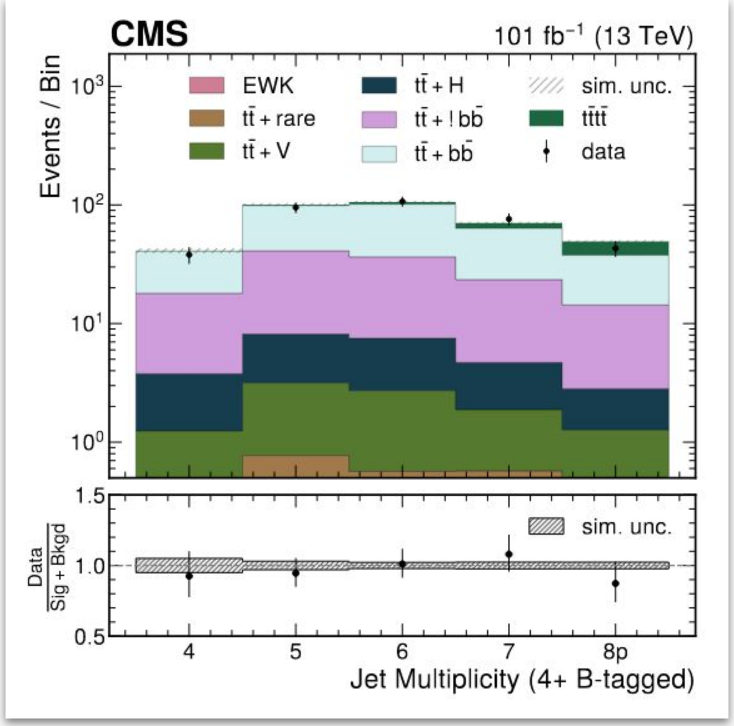
Also covered in JOKER talk by Nick Manganelli (Thursday)

Status of four top searches (CMS)

Dedicated Poster by Nick Manganelli (Monday)

NEW! 101fb^{-1}

- **OS2ℓ channel**
  - only analyze 2017 and 2018
  - 2016 measurement in *JHEP 11 (2019) 082*
- Fit H_T(jets) distributions in lepton / jet / b-jet categories
  - Low jet/b-jet categories function as CRs
- Backgrounds mostly ttbb/ttjj/ttX
  - estimated from simulation
- Measured signal-strength:
  μ(tttt) = 1.6 $^{+1.4}/_{-1.3}$ (1.3σ)



CMS four top 0ℓ/1ℓ/OS2ℓ: *CMS-PAS-TOP-21-005*

Status of four top searches (CMS)

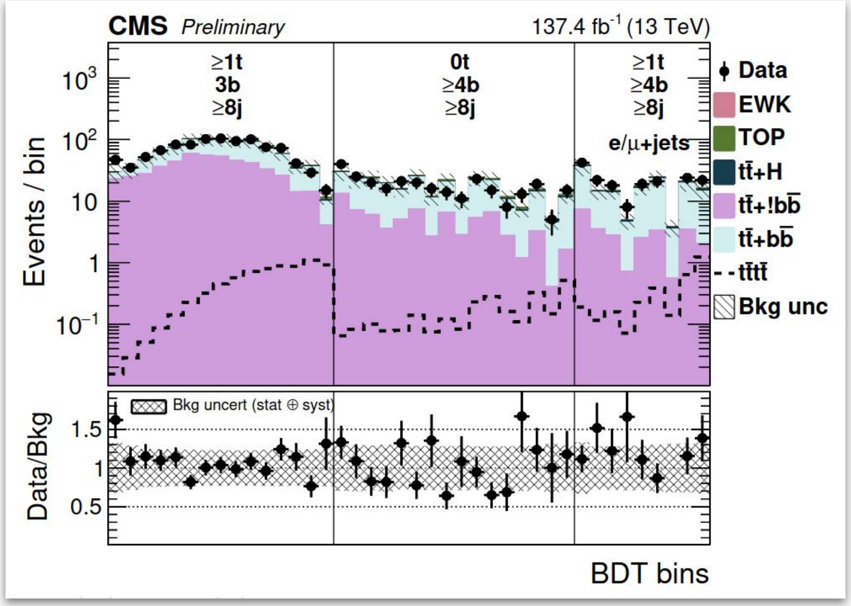
NEW! 138fb^{-1}

- **1ℓ channel**

- BDT for signal / background separation
  - ➢ Resolved top tagger as input
  - ➢ Fit BDT distributions
  - ➢ Lepton / jet / b-jet / top candidate regions

- Background dominated by ttbb
  - ➢ estimated from simulation

- Measured signal-strength:
  μ(tttt) = 1.2 ± 0.9 (1.4σ)



CMS four top 0ℓ/1ℓ/OS2ℓ: CMS-PAS-TOP-21-005

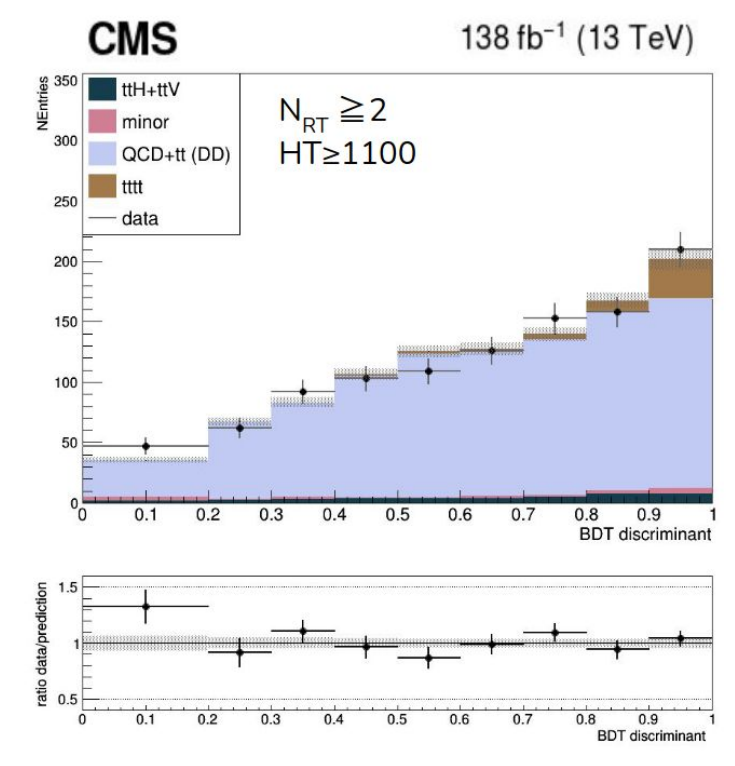
Also covered in JOKER talk by Nick Manganelli (Thursday)

Status of four top searches (CMS)

Dedicated Poster by Melissa Quinnan (Monday)

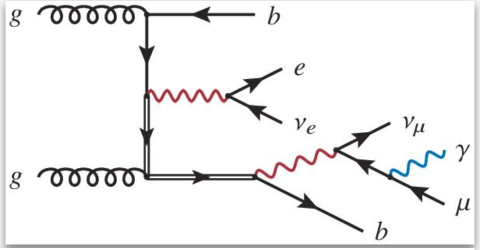
NEW! 138fb^{-1}

- **All-hadronic channel**
  - ➢ First time the all-hadronic channel is used in four top searches!
- Fit output of BDT for signal / multijet separation
  - ➢ Categories of resolved / boosted top candidates
  - ➢ Further divided into H_T(jets) bins
- Backgrounds:
  - ➢ Multijet / tt+jets → data-driven estimation
  - ➢ Minor contributions estimated from simulation
- Measured signal-strength:
  $\mu(tttt) = 5.8\ ^{+2.5}/_{-2.4}\ (2.5\sigma)$
  - ➢ High fluctuation relative to expected 0.4σ

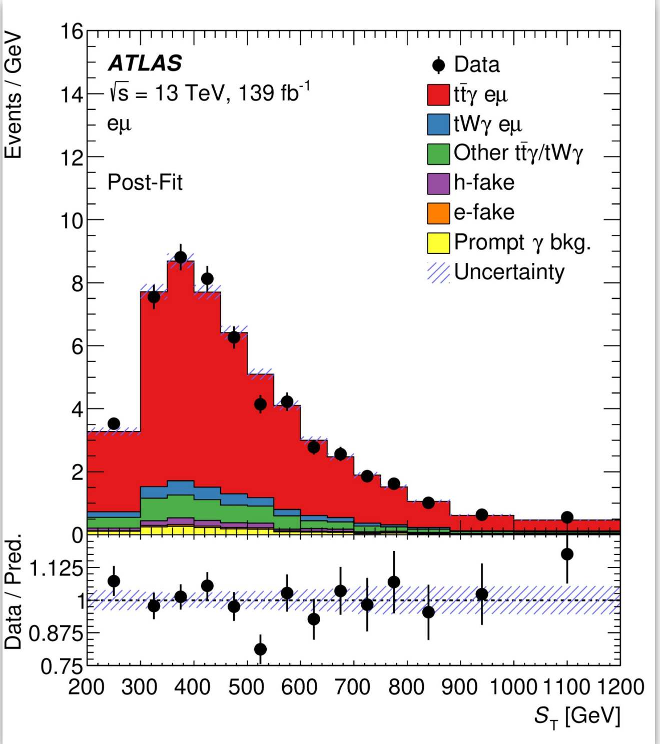


CMS four top 0ℓ/1ℓ/OS2ℓ: CMS-PAS-TOP-21-005

tt+γ cross section measurement (ATLAS)



- Combined measurement of **ttγ+tWγ in OS e+μ channel**
  - Resonant ttγ and non-resonant tWγ from pp→bWbWγ process
- Fiducial region at parton level:
  - eμ from W decays, two b-jets from top decay, one γ
- Fit S_T distribution for inclusive cross-section
- Backgrounds mostly τ-decays and non-prompt γ
  - Estimated from simulation
- Observed: **σ(ttγ) = 39.6 ± 0.8(stat) $^{+2.8}/_{-2.2}$(syst) fb**
  - Precision of 6%
  - Dominated by S&B modeling + photon identification
- Agrees well with calculations (JHEP 10 (2018) 158, JHEP 01 (2019) 188)
  σ(ttγ) = 38.5 $^{+0.56}/_{-2.18}$(scale) $^{+1.04}/_{-1.18}$(pdf) fb

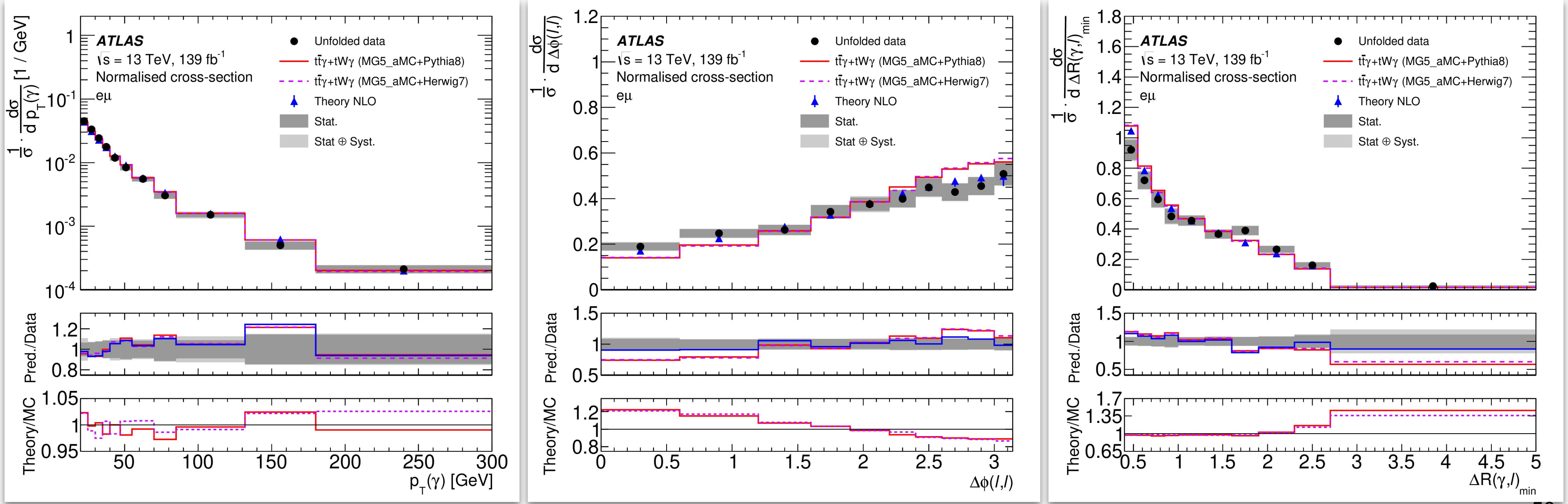


ATLAS ttγ+tWγ eμ: JHEP 09 (2020) 049

$t\bar{t}+\gamma$ cross section measurement (ATLAS)

139fb^{-1}

- Differential measurement via unfolding to parton level with RooUnfold
- Photon kinematics well-described by NLO calculation and MG5aMC simulations (sensitive to tγ coupling)
- NLO calculation describes observables related to leptons better (sensitive to tt spin correlations)

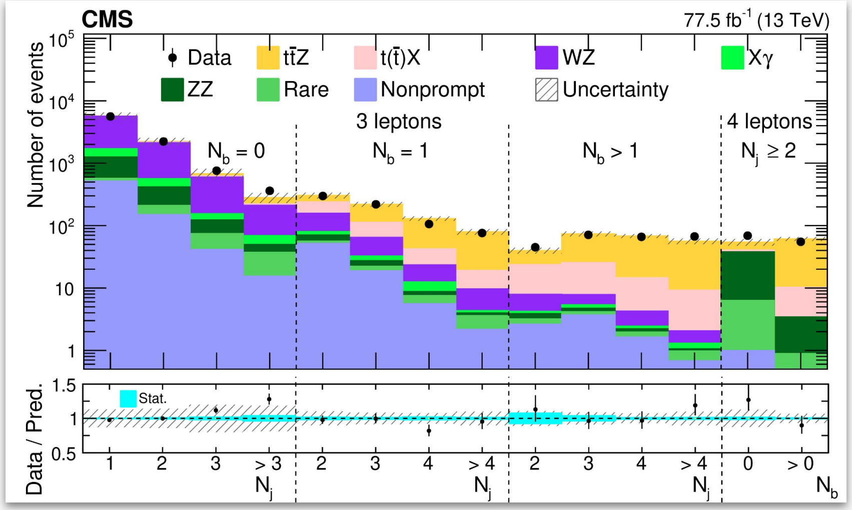


ATLAS $t\bar{t}\gamma$+tWγ eμ: JHEP 09 (2020) 049

Theory NLO: JHEP 10 (2018) 158, JHEP 01 (2019) 188

tt+Z cross section measurement (CMS)

- Measurement of **ttZ in multilepton channels**
- Fit in lepton / jet / b-jet bins



- Backgrounds:
  - ➢ Non-prompt → data-driven off-Z peak
  - ➢ WZ/ZZ → CRs on Z peaks in 3/4ℓ
  - ➢ Remaining (e.g. t(t)+X) estimated from MC

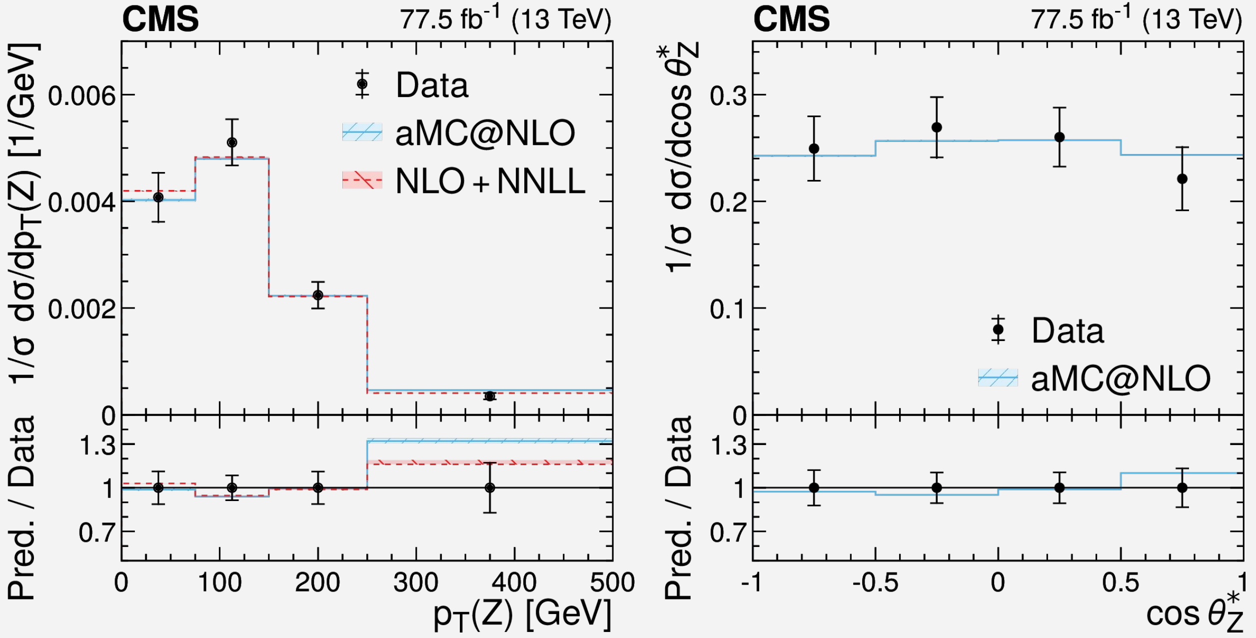
- Observed: **σ(ttZ) = 0.95 ± 0.05(stat) ± 0.06(syst) pb**
  - ➢ Precision of 8%
  - ➢ Dominated by lep. ID, PS modeling and background yields
- Agreement with NLO+NNLL calculation *(EPJC 79 (2019) 249)*
  σ(ttZ) = 0.86 $^{+0.07}/_{-0.08}$(scale) ± 0.03 (pdf+α_S) pb

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

CMS ttZ 3ℓ/4ℓ: *JHEP 03 (2020) 056*

tt+Z cross section measurement (CMS)

- Differential measurement via unfolding to parton level with TUnfold
  - Only uses the 3 lepton channel
  - OSSF lepton pair for Z reconstruction
- Probe p_T of Z boson and angle between Z and ℓ^- in Z rest frame
  - Good agreement for simulation (amC@NLO) and NLO+NNLL calculation (EPJC 79 (2019) 249)



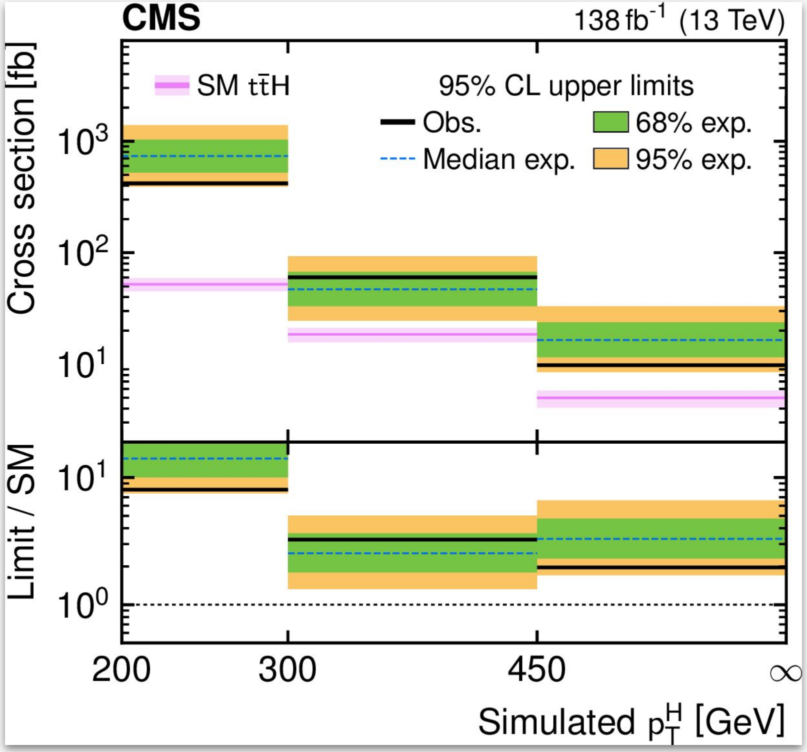
CMS ttZ 3ℓ/4ℓ: JHEP 03 (2020) 056

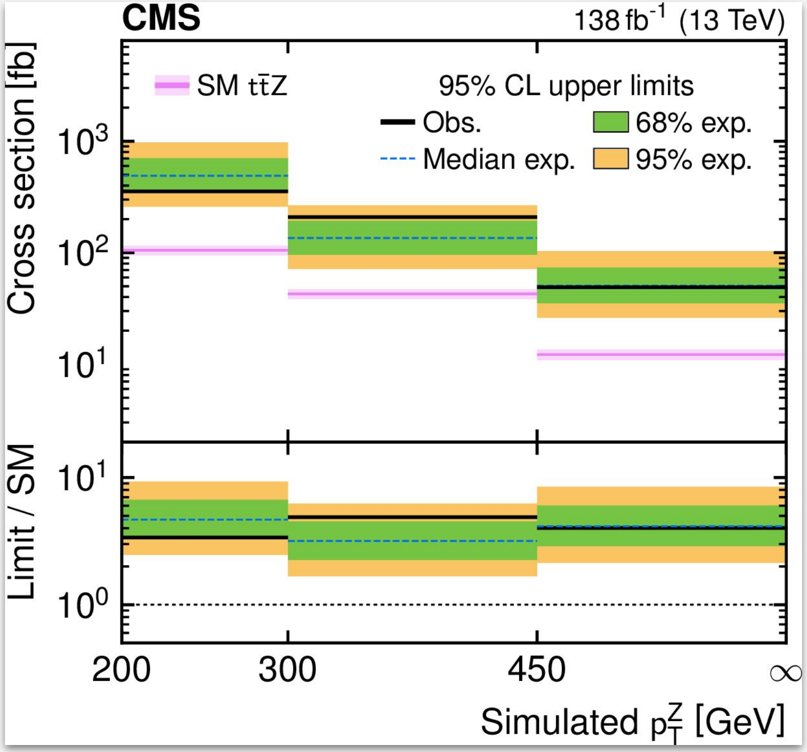
Also covered in EFT talk by Jon (Tuesday)

Boosted tt+Z/H cross section measurement (CMS)

NEW! 138fb^{-1}

- Setting differential limits on p_T of Z and H boson
  - ➢ Higher sensitivity on H than Z due to large H→bb branching fraction





CMS boosted ttZ/H: *CMS-TOP-21-003* (submitted to PRD)

tt+W cross section measurement (ATLAS)

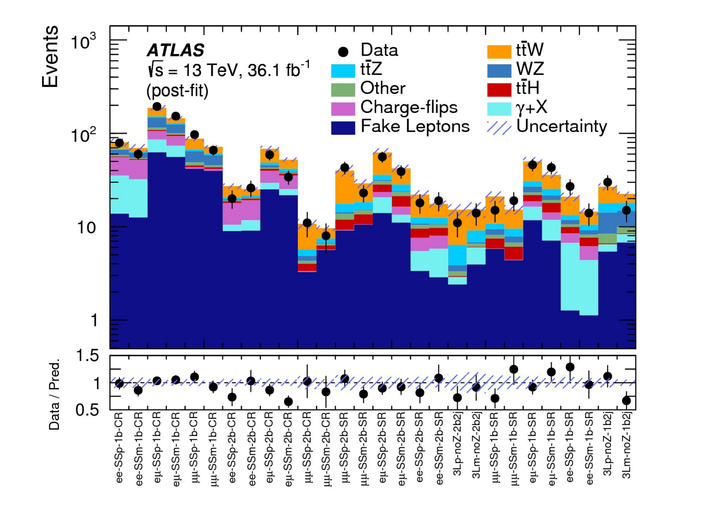
36fb^{-1}

- Measurement of **ttW and ttZ in multilepton channels**
  - ➢ ttZ measurement superseded by *EPCJ 81 (2021) 737*
- SS2ℓ and 3ℓ regions targeting ttW:
  - ➢ SS2ℓ split per charge and lepton flavors, b-jets
  - ➢ 3ℓ split in on- and off-Z peak for ttW and ttZ and jet and b-jet regions
- Backgrounds:
  - ➢ WW/WZ/ZZ → CRs
  - ➢ Non-prompt leptons → data-driven
  - ➢ Others estimated from simulation
- Observed ttW cross section in 2D fit of ttW and ttZ:

σ(ttW) = 0.87 ± 0.13(stat) ± 0.14(syst) pb

  - ➢ Precision of 22%
  - ➢ Limited by signal modeling and data statistics

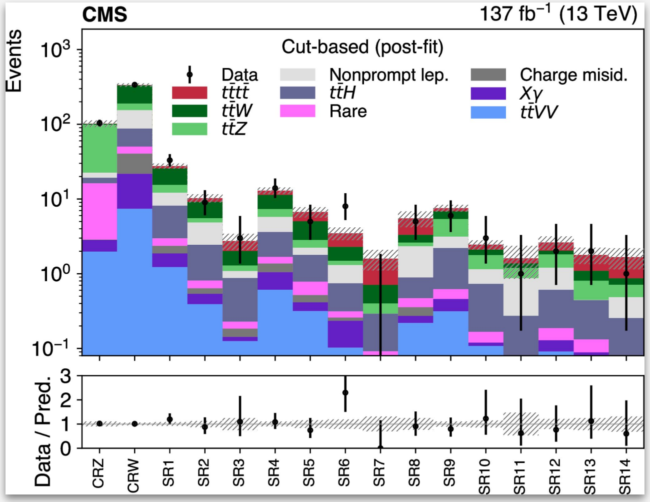
Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	–
3ℓ $t\bar{t}Z$	1.08 ± 0.18	–
2ℓ-SS and 3ℓ $t\bar{t}W$	–	1.41 ± 0.33
4ℓ	1.21 ± 0.29	–



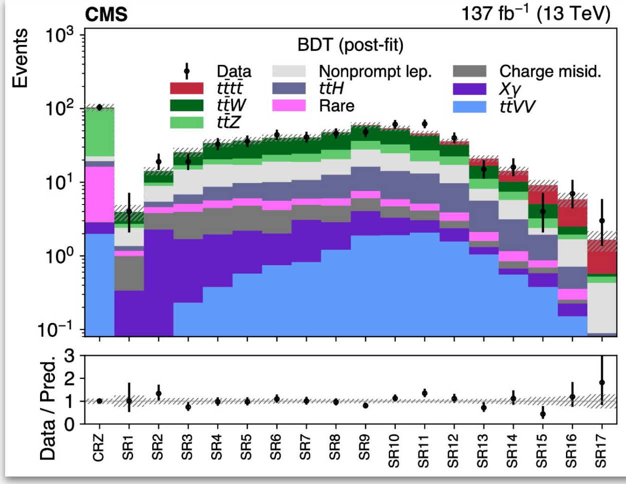
ATLAS ttW/ttZ 2ℓ/3ℓ/4ℓ: *PRD 99 (2019) 072009*

Status of four top searches (CMS)

- **Multi-lepton + SS2ℓ channel**
- Two analysis strategies
  - ➢ Cut-based: Separate lepton / jet / b-jet bins
  - ➢ BDT-based: BDT for signal identification in full region



- Backgrounds:
  - ➢ ttW/ttZ → CRs with less jets / on Z peak
  - ➢ Non-prompt → data-driven estimation



- Measured signal-strength for BDT analysis:
  $\mu(tttt) = 1.1\ ^{+0.5}/_{-0.4}\ (2.5\sigma)$
  - ➢ Higher sensitivity than cut-based analysis (1.7σ)
  - ➢ Statistically limited

CMS four top SS2ℓ/3ℓ+: [EPCJ 80 (2020) 75]