Top-Quark Production at the LHC

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on behalf of the ATLAS and CMS Collaborations

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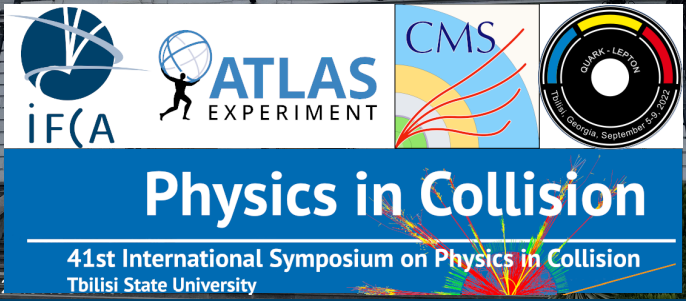

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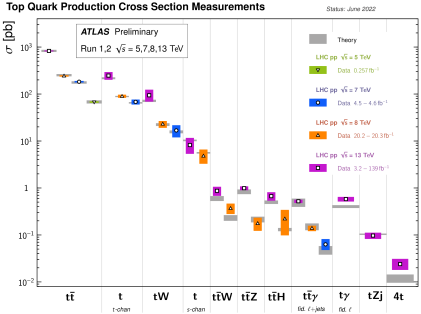
ATLAS publications

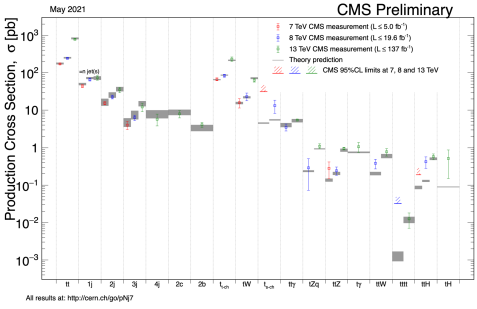
- Measurement of the $t\bar{t}$ production cross-section in the lepton+jets channel at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ATLAS experiment. Phys. Lett. B 810 (2020) 135797
- Measurement of the $t\bar{t}$ production cross-section and lepton differential distributions in $e\mu$ dilepton events from pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ATLAS detector Eur. Phys. J. C 80 (2020) 528
- Measurement of the $t\bar{t}$ production cross-section in pp collisions at $\sqrt{s} = 5.02\,\mathrm{TeV}$ with the ATLAS detector arXiv:2207.01354
- Differential $t\bar{t}$ cross-section measurements using boosted top quarks in the all-hadronic final state with $139\,\mathrm{fb}^{-1}$ of ATLAS data arXiv:2205.02817
- Measurements of differential cross-sections in top-quark pair events with a high transverse momentum top quark and limits on beyond the Standard Model contributions to top-quark pair production with the ATLAS detector at $\sqrt{s} = 13\,\mathrm{TeV}$ JHEP 06 (2022) 063JHEP 06 (2022) 063
- Measurement of the $t\bar{t}t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ATLAS detector JHEP 11 (2021) 118
- Measurements of the inclusive and differential production cross sections of a top-quark-antiquark pair in association with a Z boson at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ATLAS detector Eur. Phys. J. C 81 (2021) 737
- Observation of the associated production of a top quark and a Z boson in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ATLAS detector JHEP 07 (2020) 124
- Measurements of inclusive and differential cross-sections of combined $t\bar{t}\gamma$ and $tW\gamma$ production in the $e\mu$ channel at $13\,\mathrm{TeV}$ with the ATLAS detector JHEP 09 (2020) 049

CMS publications

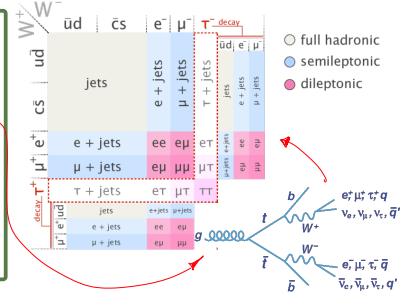
- Combination of inclusive top-quark pair production cross-section measurements using ATLAS and CMS data at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$ arXiv:2205.13830
- Measurement of the inclusive and differential $\mathrm{t\bar{t}\gamma}$ cross sections in the dilepton channel and effective field theory interpretation in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ JHEP 05 (2022) 091
- Measurement of differential $\mathrm{t\bar{t}}$ production cross sections in the full kinematic range using lepton+jets events from proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ Phys. Rev. D 104 (2021) 092013
- Measurement of differential $\mathrm{t\bar{t}}$ production cross sections using top quarks at large transverse momenta in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ Phys. Rev. D 103 (2021) 052008
- Measurement of the cross section of top quark-antiquark pair production in association with a W boson in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ arXiv:2208.06485
- Measurement of the inclusive and differential $\mathrm{t\bar{t}\gamma}$ cross sections in the dilepton channel and effective field theory interpretation in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ JHEP 05 (2022) 091
- Measurement of the inclusive and differential $\mathrm{t\bar{t}\gamma}$ cross sections in the single-lepton channel and EFT interpretation at $\sqrt{s} = 13\,\mathrm{TeV}$ JHEP 12 (2021) 180
- Measurement of inclusive and differential cross sections for single top quark production in association with a W boson at $\sqrt{s} = 13\,\mathrm{TeV}$ CMS-PAS-TOP-21-010
- Measurement of differential cross sections for the production of top quark pairs and of additional jets in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ CMS-PAS-TOP-20-006
- Search for central exclusive production of top quark pairs in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with tagged protons CMS-PAS-TOP-21-007

Top Quark Production

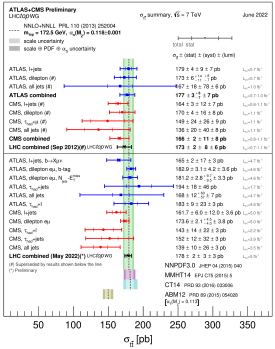


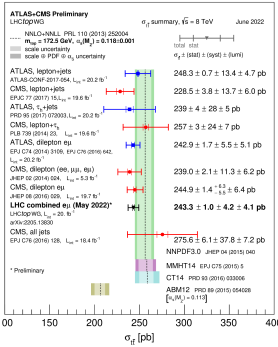


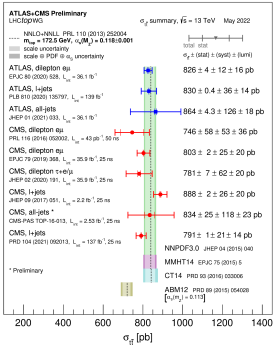
- Top-quark is the heaviest particle (so far) $\approx 173.4\,\mathrm{GeV}$
- decays before hadronization $\approx 5 \times 10^{-25}\,\mathrm{s}$
- Almost all the times decays into a W boson and a b quark
- Rich top physics program at the LHC
- $t\bar{t}$ cross section at different energies: 5.02, 7, 8, 13 TeV
- single top processes
- $t\bar{t}$+X $\rightarrow$ Couplings!!



$t\bar{t}$ Cross Section



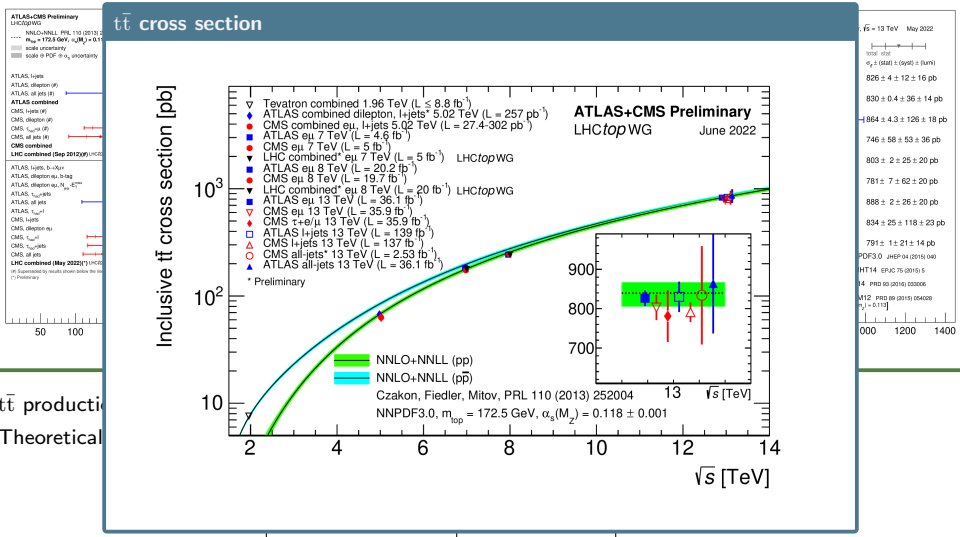




1. $t\bar{t}$ production at the LHC is dominated by gg fusion
2. Theoretical predictions at NNLO+NNLL soft gluon resummation

$\sqrt{s}$ [TeV]	Central Value [pb]	Scale Unc.[pb]	PDF+α_s Unc.[pb]
5.02	69.5	2.3	2.9
7	179.6	6.2	6.1
8	256.0	8.9	8.0
13	833.9	30.0	21.0
13.6	923.6	33.4	22.8

$t\bar{t}$ Cross Section



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2. Theoretical

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13	833.9	30.0	21.0
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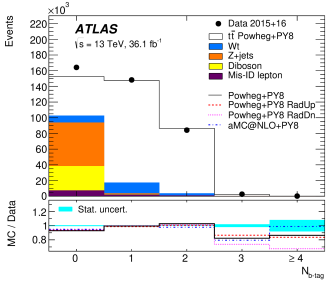
Inclusive $t\bar{t}$ Cross Section

1. Inclusive measurements: $e\mu$ is the golden channel
   - $\ell + \text{jets}$ also very precise
2. High purity of $t\bar{t}$ events
3. Dominated by systematic uncertainties
4. Really high precision compared with the theoretical calculations
5. Additional m_{top} and α_s

Inclusive $\sigma_{t\bar{t}}$ measurement by ATLAS (μe):

$826.4 \pm 3.6(\text{stat.}) \pm 11.5(\text{syst.}) \pm 15.7(\text{Lumi.}) \pm 1.9(\text{beam})\ \text{pb}$

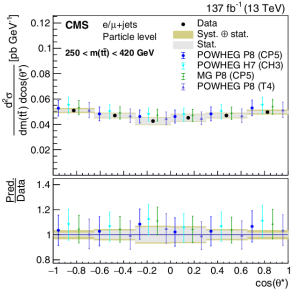
$$\frac{N_1(\sigma_{t\bar{t}}\varepsilon_b)}{N_2(\sigma_{t\bar{t}}\varepsilon_b)}$$



Inclusive $\sigma_{t\bar{t}}$ measurement by CMS ($\ell + \text{jets}$):

$791 \pm 1(\text{stat.}) \pm 21(\text{syst.}) \pm 14(\text{Lumi.})\ \text{pb}$

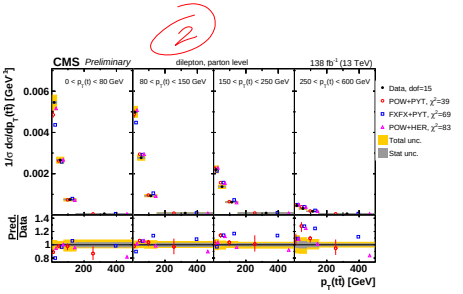
$$\sum_{i=\text{bins}} d\sigma^i_{t\bar{t}}$$

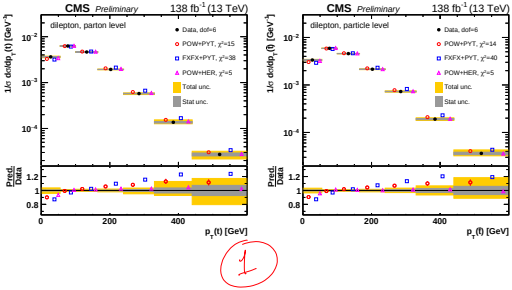


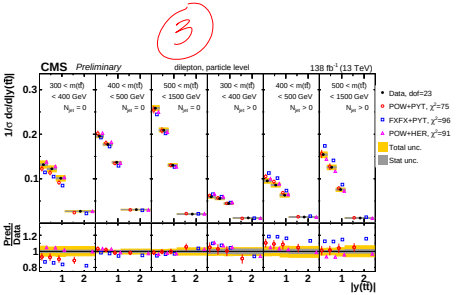
Differential $t\bar{t}$ Cross Section

CMS dilepton channel

- $t\bar{t}$ cross section as function of 1/2/3 kinematic variables
- Kinematic variables of the $t\bar{t}$ system, $t/\bar{t}$, decay products and additional jets.
- Distributions at particle/parton level
- Some overestimations of data by the MC



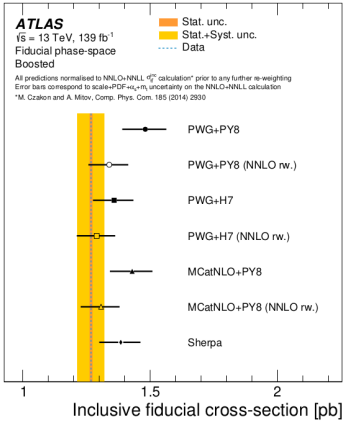


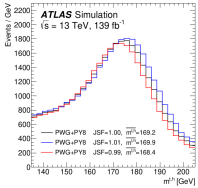


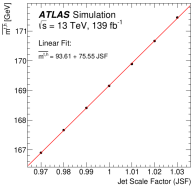
Differential $t\bar{t}$ Cross Section: Boosted Regime

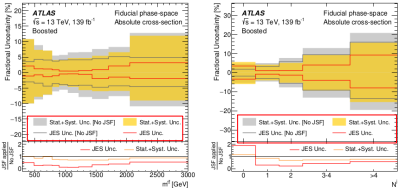
ATLAS $\ell + \text{jets}$ channel

- $t\bar{t}$ events containing a boosted top quark
  - Large radius jets ($R = 1.0$) with $p_T > 350\,\text{GeV}$
  - Other top $\rightarrow \ell + \text{jets}$
- Full reconstruction of the $t\bar{t}$ system
- Uncertainties associated to the JES are reduced by means of the top-quark mass
- Large radius jets ($R = 1.0$)
- Limits in NP
- Parton-level reweight to match NNLO QCD improves the Data/MC agreement

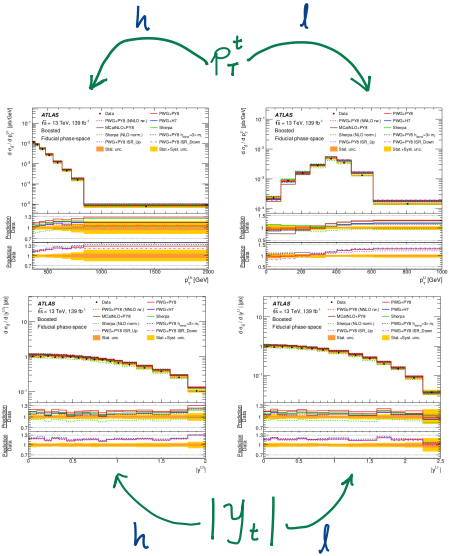


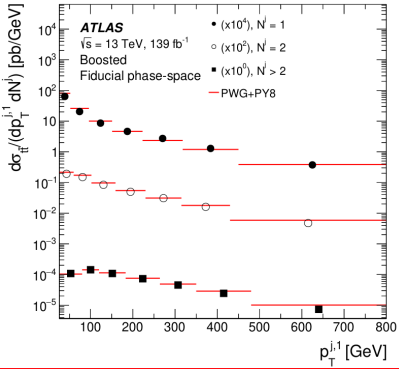


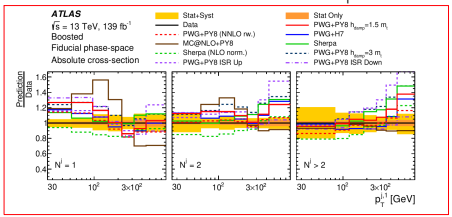




Differential $t\bar{t}$ Cross Section: Boosted Regime







Differential $t\bar{t}$ Cross Section: Boosted Regime

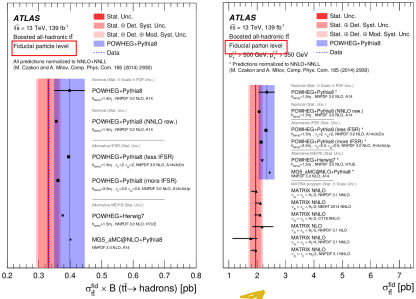
ATLAS all hadronic channel

- Final state with highly boosted top quarks: Test QCD $t\bar{t}$ production process at the TeV scale
- DNN to identify top-quark jets
- Unfolding to particle/parton-level
- Large radius jets ($R = 1.0$)
  - small-R $R = 0.4$
  - variable-R $R = 0.02 \rightarrow R = 0.4$
- High p_T for large-R jets $p_T > 500\,\mathrm{GeV}/p_T > 350\,\mathrm{GeV}$
- Results compatibles with the MC prediction (20% lower) within the uncertainties
- Additional differential distributions for sensitive variables

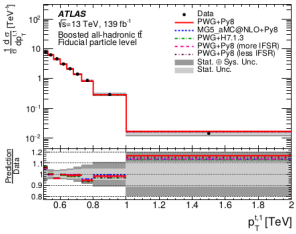
Source	Relative Uncertainty [%]
Top-tagging	7.8
JES ⊕ JER	4.2
JMS ⊕ JMR	1.1
Flavour tagging	2.9
Alternative hard-scattering model	0.9
Alternative parton-shower model	4.3
ISR/FSR + scale	4.9
PDF	0.8
Luminosity	1.7
MC sample statistics	0.4
Total systematic uncertainty	11.8
Statistical uncertainty	1.0
Total uncertainty	11.8

$$\sigma^{t\bar{t},\mathrm{fid}}_{\mathrm{particle}} \times B(t\bar{t} \rightarrow \mathrm{hadrons}) = 331 \pm 3(\mathrm{stat.}) \pm 39(\mathrm{syst.})\ \mathrm{fb}$$

$$\sigma^{t\bar{t},\mathrm{fid}}_{\mathrm{parton}} = 1.94 \pm 0.02(\mathrm{stat.}) \pm 0.25(\mathrm{syst.})\ \mathrm{pb},$$



Differential $t\bar{t}$ Cross Section: Boosted Regime



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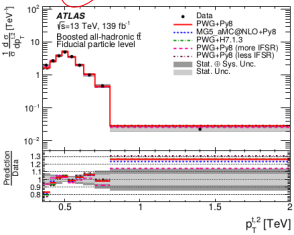

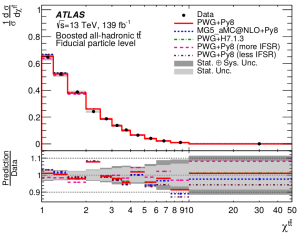

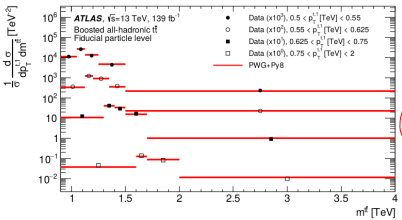

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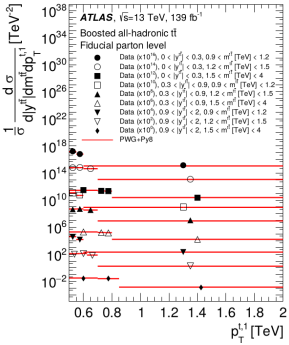

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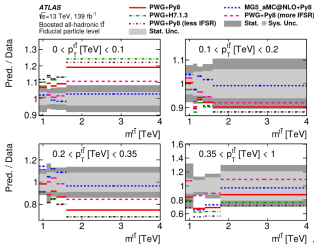
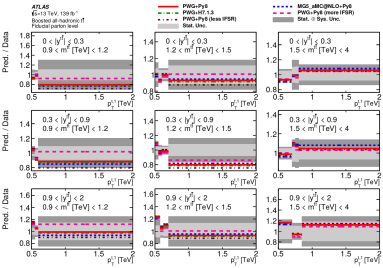
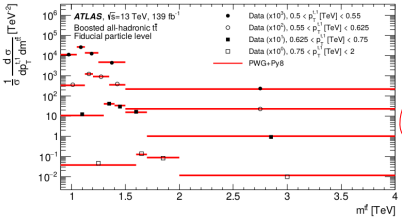
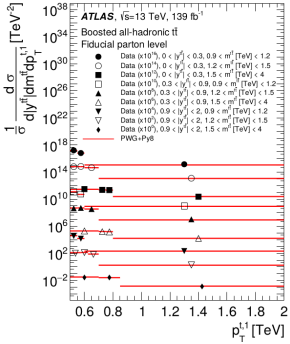
Differential $t\bar{t}$ Cross Section: Boosted Regime









2

3

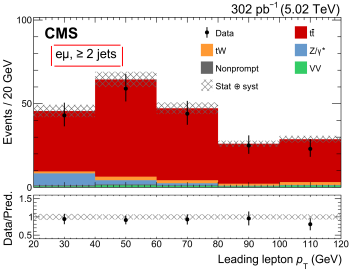
Cross Section Measurements at 5.02 TeV

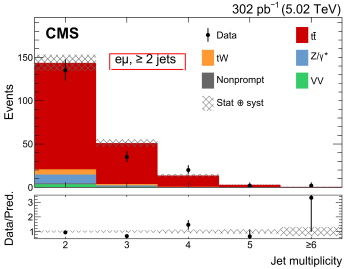
$\sigma_{t\bar{t}}$ at 5.02 TeV

- Measurement performed with 2017 data.
- PDF Constraint
- Dilepton channel
- Cut and count approach
- Result combined with previous $\ell + \text{jets}$ @ 5.02 TeV
- Improvement from previous measurement: from 13%(2015) $\rightarrow$ 7.9%(2017+2015)

Uncertainties

Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}(\%)$
JES	2.2
Drell–Yan	1.8
Electron efficiency	1.6
L1 prefiring	1.4
Trigger efficiency	1.3
JER	1.2
Final-state radiation	1.1
h_{damp}	1.0
Total systematic uncertainty	4.3
Integrated luminosity	1.9





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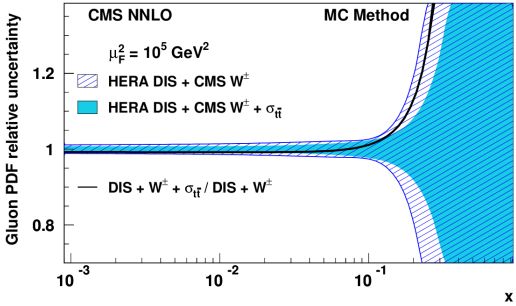
Uncertainties

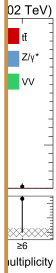
Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}(\%)$
JES	2.2
Drell–Yan	1.8
	1.6
	1.4
	1.3
	1.2
	1.1
	1.0
	4.3
	1.9

CMS $t\bar{t}$ at 5.02 GeV

$$\sigma_{t\bar{t}}(\ell\ell) = 60.7 \pm 5.0(\text{stat.}) \pm 2.8(\text{syst.}) \pm 1.1(\text{Lumi.})\ \text{pb}$$

$$\sigma_{t\bar{t}}(\ell\ell + \ell + \text{jets}) = 63.0 \pm 4.1(\text{stat.}) \pm 3.0(\text{syst+lumi})\ \text{pb}$$





Cross Section Measurements at 5.02 TeV

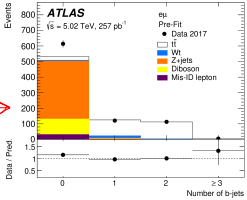
$\sigma_{t\bar{t}}$ at 5.02 TeV ATLAS

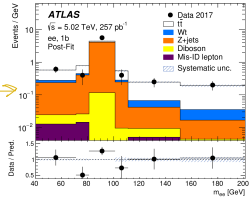
- $\sigma_{t\bar{t}}$ 12x smaller than at 13 TeV
- $q\bar{q}$ fraction increased from 11% to 25%
- Measurement performed with 2017 data
- Dilepton and $\ell + \text{jets}$ channels
- $\ell\ell$ and $\ell + \text{jets}$ combination by Convino

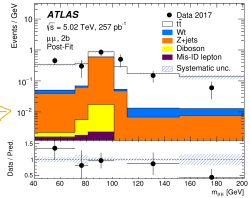
Dilepton

- μe: Similar approach 13 TeV
- $\mu\mu + ee$: Using the $m_{\ell\ell}$ as well
- Unc. in the $\ell\ell$ measurement improves by using SF $\sim 1\%$

$$\sigma_{t\bar{t}}(\ell\ell) = 65.7 \pm 4.5(\text{stat.}) \pm 1.6(\text{syst.}) \pm 1.2(\text{Lumi.}) \pm 0.2(\text{beam})\,\text{pb}$$







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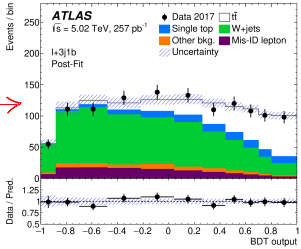
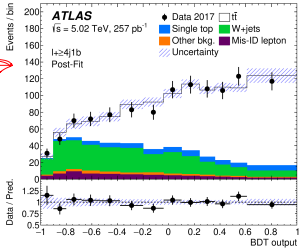
Lepton+jets

- $\ell + \text{jets}$: Fit over BDTs
- Multiple signal regions (6) by N_{jet} and $N_{\text{b-tag}}$
- Smaller top modelling unc than 13 TeV

$$\sigma_{t\bar{t}}(\ell\ell) = 68.2 \pm 0.9(\text{stat.}) \pm 2.9(\text{syst.}) \pm 1.1(\text{Lumi.}) \pm 0.2(\text{beam})\ \text{pb}$$

4% !!!

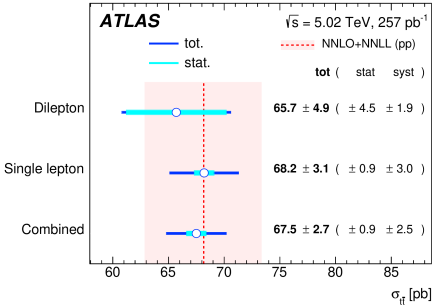


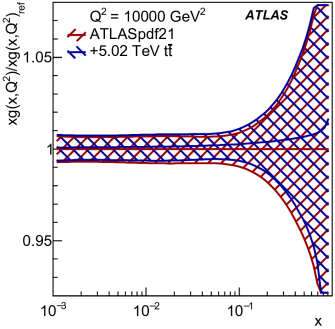


Cross Section Measurements at 5.02 TeV

$\sigma_{t\bar{t}}$ at 5.02 TeV ATLAS

ATLAS $t\bar{t}$ at 5.02 GeV





Combination: 7 and 8 TeV

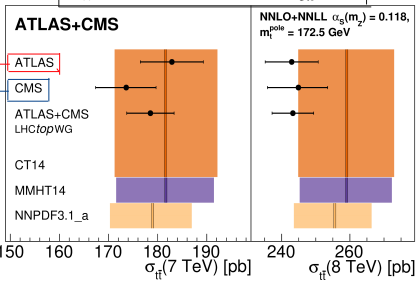
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\,\text{TeV}) = 178.5 \pm 4.7\ \text{pb}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\,\text{TeV}) = 243.3^{+6.0}_{-5.9}\ \text{pb},$$

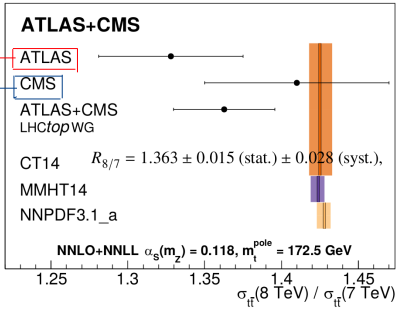
ATLAS + CMS

- $e\mu$ channel with the full RunI dataset
- Combination done by means of a χ^2 minimization with Convino
- Each measurement is performed with different approaches:
  - CMS: Profile likelihood fit to final state observables (N_j, N_b, p_T^{jet})
  - ATLAS: Tag-counting (including the $\mathcal{E}_b$)
- Key point: Consideration of all correlations between the uncertaities
- Includes extraction of m_t^{pole} and α_s

$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\,\text{TeV}) = 182.9 \pm 3.1\ (\text{stat.}) \pm 4.2\ (\text{exp.+theo.}) \pm 3.6\ (\text{lumi.})\ \text{pb and}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\,\text{TeV}) = 242.9 \pm 1.7\ (\text{stat.}) \pm 5.5\ (\text{exp.+theo.}) \pm 5.1\ (\text{lumi.})\ \text{pb},$$

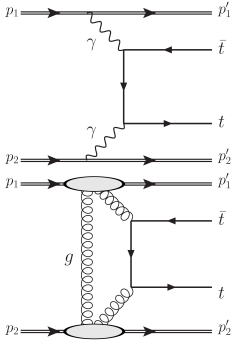
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\,\text{TeV}) = 173.6 \pm 2.1\ (\text{stat.})^{+4.5}_{-4.0}\ (\text{exp.+theo.}) \pm 3.8\ (\text{lumi.})\ \text{pb and}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\,\text{TeV}) = 244.9 \pm 1.4\ (\text{stat.})^{+6.3}_{-5.5}\ (\text{exp.+theo.}) \pm 6.4\ (\text{lumi.})\ \text{pb},$$

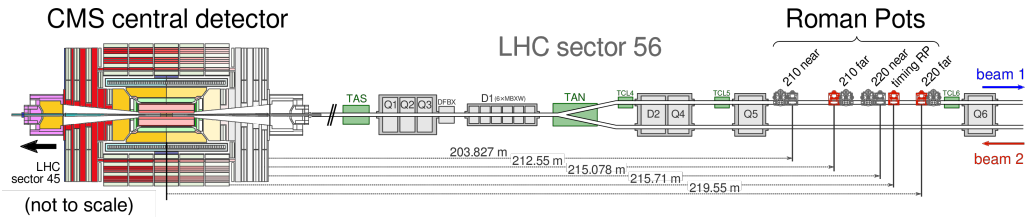




Search for central exclusive $t\bar{t}$

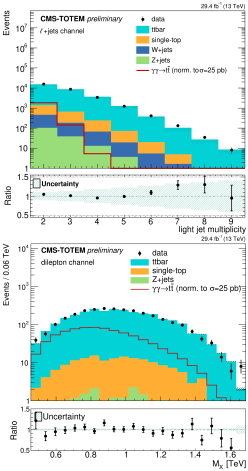
- Exclusive central production via pp $\rightarrow$ pt$\bar{t}$p
- 2017 data $\rightarrow \mathcal{L} = 29.4\,\mathrm{fb}^{-1}$. Final state with ℓ
- Alternative production mode of top by exchange of colorless particles:
  - photons or pomerons
- Both protons remain intact after interaction, energy fraction transferred to tt pair ξ
- Observation expected at HL-LHC
  - BSM physics could enhance σ
- Forward protons detected with CMS-TOTEM Precision Proton Spectrometer (CT-PPS)

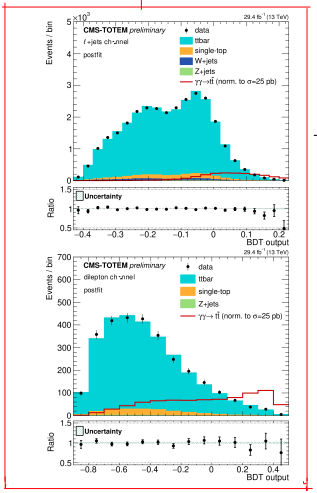


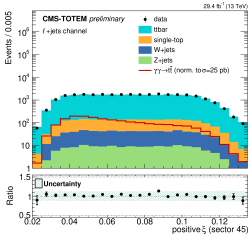


Search for central exclusive $t\bar{t}$

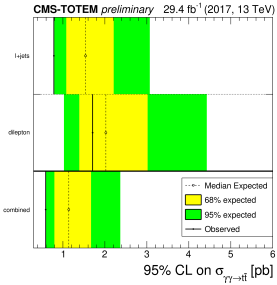
- Full kinematic reconstruction of the $t\bar{t}$ system
- BDT to discriminate signal (exclusive $t\bar{t}$) from background (inclusive $t\bar{t}$ + PU protons)







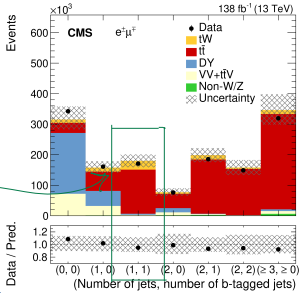
Channel	Expected [pb]	Observed [pb]
$\ell\ell$	2.02	1.70
ℓ + jets	1.54	0.78

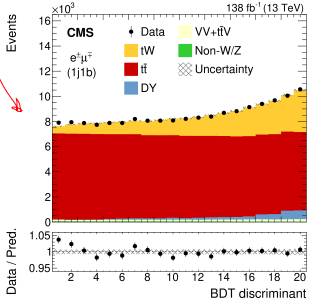


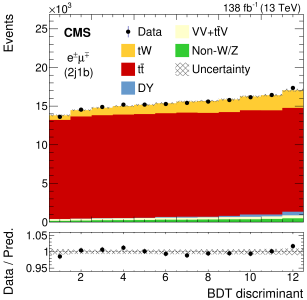
tW Cross Section

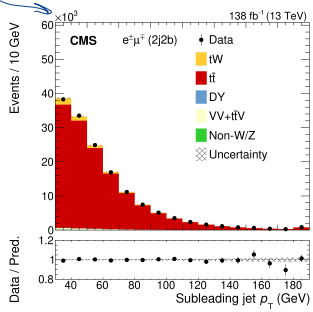
Inclusive tW

- Full Run II measurement: Inclusive + Differential cross section in the $e\mu$ channel
- Selected events classified by N_j and N_b:
- 1j1b enriched signal region (20% tW)
- BDTs to further separation from $t\bar{t}$
- Maximum likelihood fit over BDTs and p_T^{j2}







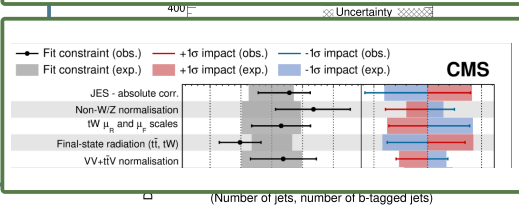


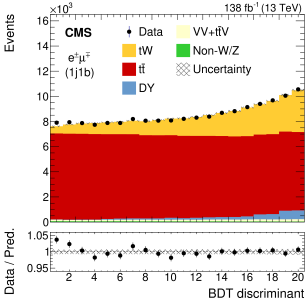
tW Cross Section

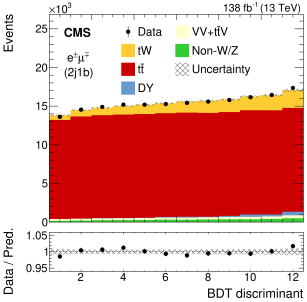
Inclusive tW

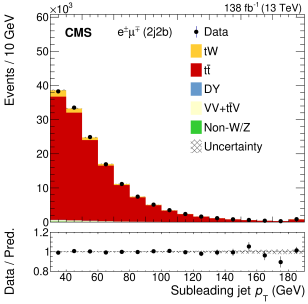
- Full Run II measurement: Inclusive + Different cross section in the $e\mu$ channel
- Selected events classified by N_j and N_b:
- 1j1b enriched signal region (20% tW)
- BDTs to further separation from $t\bar{t}$
- Maximum likelihood fit over BDTs and p_T^{j2}

$$\sigma_{tW} = 79.2 \pm 0.9(\text{stat.})^{+7.7}_{-8.0}(\text{syst.}) \pm 1.2(\text{Lumi.})\,\text{pb}$$
$$\sigma_{tW}^{SM}(\text{NNLO}) = 71.7 \pm 1.8(\text{scale}) \pm 3.4(\text{PDF})\,\text{pb}$$





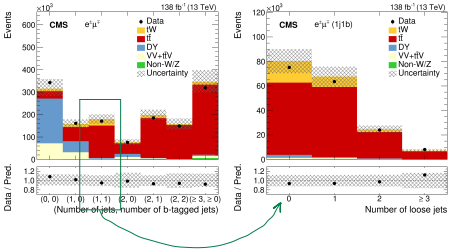


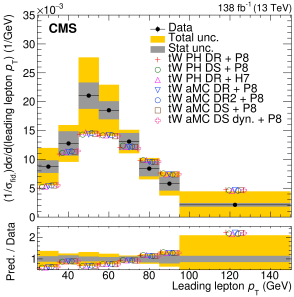


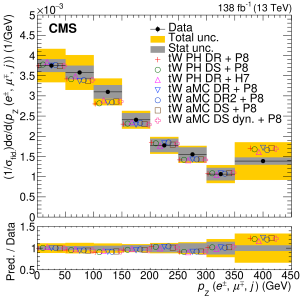
tW Cross Section

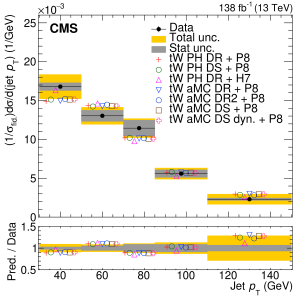
Differential tW

- Full Run II measurement: Inclusive + Differential cross section in the $e\mu$ channel
- Only 1j1b region + additional cuts
- Unfolding to the particle level for 6 physical observables
- Some tensions in the p_T^j, p_T^ℓ and $m_{\ell j}$
- Uncertainties between 10 and 50%





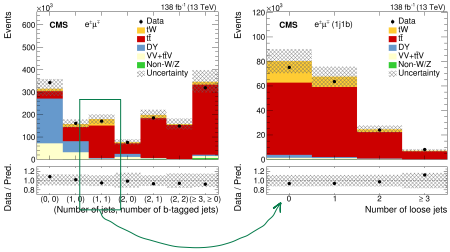


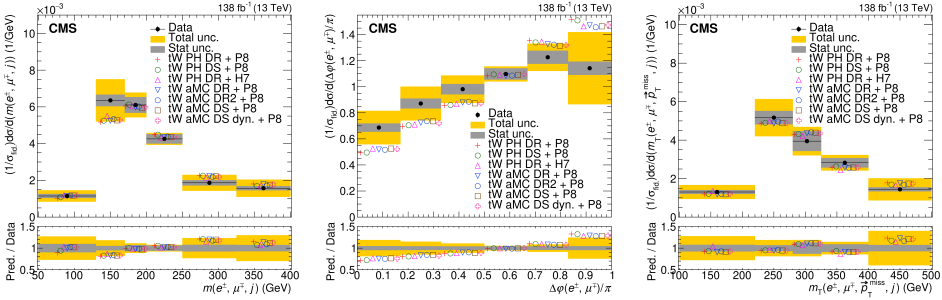


tW Cross Section

Differential tW

- Full Run II measurement: Inclusive + Differential cross section in the $e\mu$ channel
- Only 1j1b region + additional cuts
- Unfolding to the particle level for 6 physical observables
- Some tensions in the p_T^j, p_T^ℓ and $m_{\ell j}$
- Uncertainties between 10 and 50%

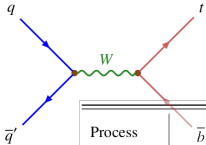




s-channel production

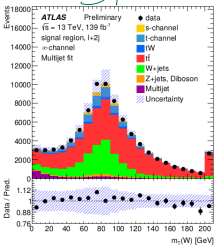
Inclusive s-channel at 13 TeV

- Most difficult single top process at LHC
- After event selection ($1\ell + \geq 2$j): 130k events with only 3% s-channel!!!
- 4 different regions: SR(s-ch) + CR(W+Jets) + 2 CR($t\bar{t}$)
- Discriminant based on matrix element calculations (MEM):
  - s-channel from $t\bar{t}$ and W+Jets
- $\sigma_{\text{s-ch}}$ extracted by a binned profile ML of MEM

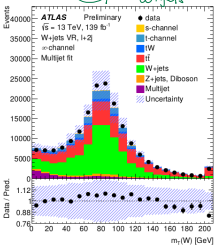


Process	Event yield Pre-fit	Post-fit
s-channel	$4\,200 \pm 710$	$3\,700 \pm 1\,100$
t-channel	$13\,000 \pm 2\,000$	$15\,000 \pm 2\,300$
tW	$3\,680 \pm 970$	$4\,250 \pm 1\,100$
$t\bar{t}$	$76\,000 \pm 12\,000$	$70\,600 \pm 4\,200$
W+jets	$21\,500 \pm 2\,900$	$32\,200 \pm 5\,000$
Z+jets, VV	$2\,400 \pm 1\,400$	$2\,900 \pm 1\,600$
Multijet	$2\,150 \pm 650$	$1\,700 \pm 540$
Total	$123\,000 \pm 17\,000$	$130\,310 \pm 620$
Data	130 310	

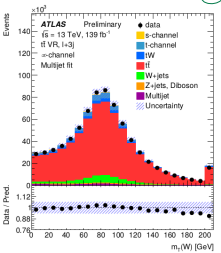
SR

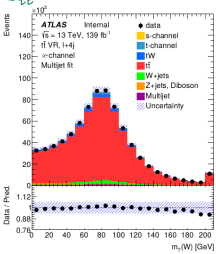


CR W+jets

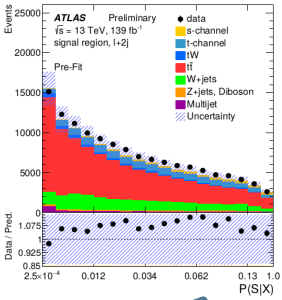


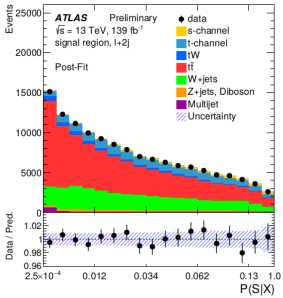
CR $t\bar{t}$





s-channel Production

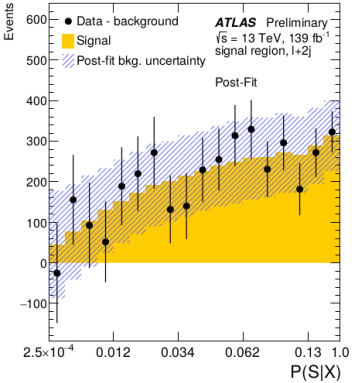




Largest uncertainties

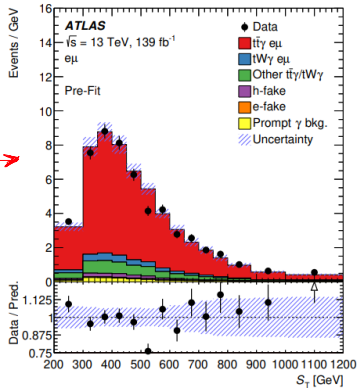
Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ normalisation	+24/−17
Jet energy resolution	+18/−12
Jet energy scale	+18/−13
Other s-channel modelling sources	+18/−8
Top-quark processes ISR/FSR	+13/−11
MC statistics	+13/−11
Other $t\bar{t}$ shape modelling sources	+12/−10
Flavour tagging	+12/−10

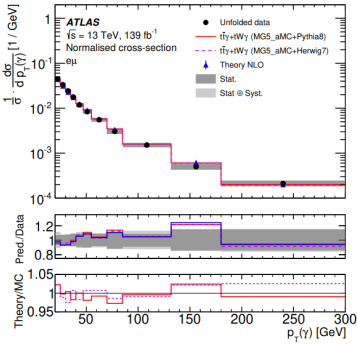
$$\sigma_{\text{s-ch}} = 8.2 \pm 0.6(\text{stat.})^{+3.4}_{-2.8}(\text{syst.})\,\text{pb}$$
$$\sigma^{SM}_{\text{s-ch}} = 10.32 \pm 0.40\,\text{pb}$$

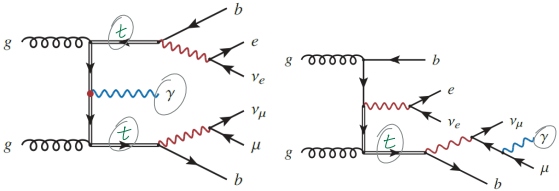


$t\bar{t}\gamma$ and $tW\gamma$ Production

- Test of the $t\gamma$ electroweak coupling
- Inclusive + differential measurements
- $\mu e + \gamma + \geq 2$ jets + ≥ 1 b-tag
- Inclusive measurement from binned PL over S_T
- Results in agreement with the SM predictions



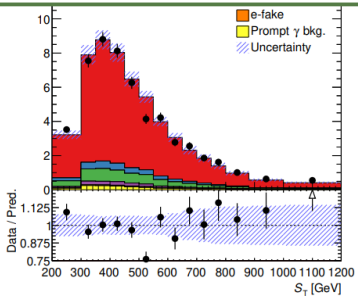


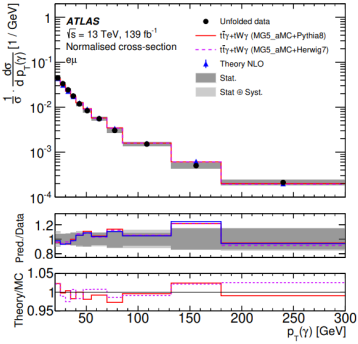


$t\bar{t}\gamma$ and $tW\gamma$ Production

- Test of the $t\gamma$ electroweak coupling
- Inclusive + differential measurements
- $\mu e + \gamma + \geq 2$ jets $+ \geq 1$ b-tag
- Inclusive measurement from binned PL over S_T
- Results in agreement with the SM predictions

$$\sigma^{\text{Fid}}_{t\bar{t}\gamma/tW\gamma} = 39.6 \pm 0.8(\text{stat.})^{+2.6}_{-2.2}(\text{syst.})\ \text{pb}$$
$$\sigma^{\text{SM-Fid}}_{t\bar{t}\gamma/tW\gamma} = 38.50^{+0.56}_{-2.18}(\text{scale})^{1.04}_{1.18}(\text{PDF})\ \text{pb}$$

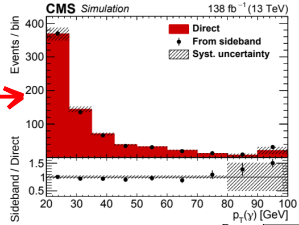


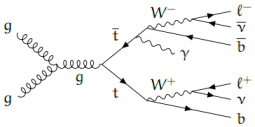


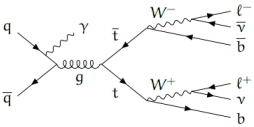
Category	Uncertainty
$t\bar{t}\gamma/tW\gamma$ modelling	3.8%
Background modelling	2.1%
Photons	1.9%
Luminosity	1.8%
Jets	1.6%
Pile-up	1.3%
Leptons	1.1%
Flavour-tagging	1.1%

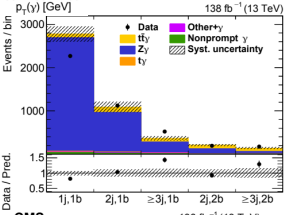
$t\bar{t}\gamma$ Production

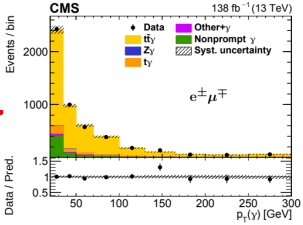
- Dilepton channel + 1 γ + ge1b-tag
- Background splited into:
  - Prompt γ from Zγ
  - Nonprompt extracted from data
- Inclusive $\sigma_{t\bar{t}\gamma}$ from a PLF to the $p_T{}^{\gamma}$
- Differential $\sigma_{t\bar{t}\gamma}$ for 12 observables

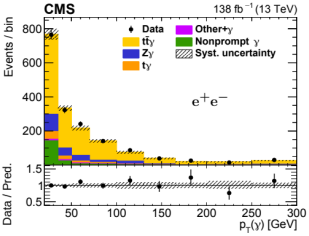


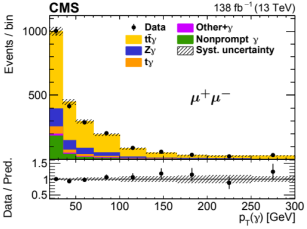






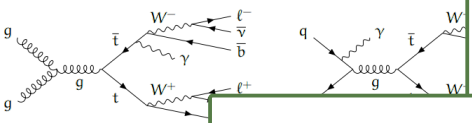


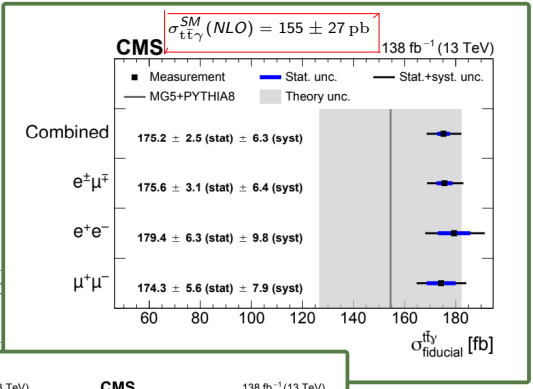


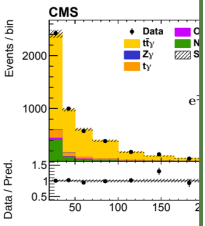


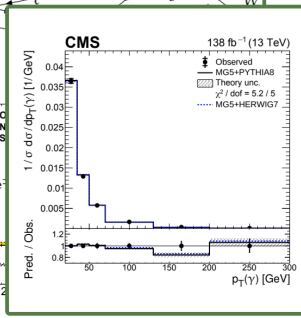
$t\bar{t}\gamma$ Production

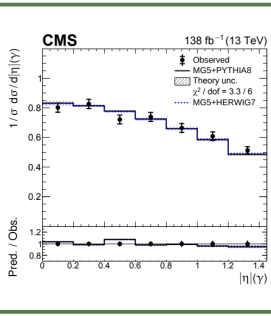
- Dilepton channel + 1 γ + ge1b-tag
- Background splited into:
  - Prompt γ from Zγ
  - Nonprompt extracted from data
- Inclusive $\sigma_{t\bar{t}\gamma}$ from a PLF to the $\mathrm{p_T}^{\gamma}$
- Differential $\sigma_{t\bar{t}\gamma}$ for 12 observables

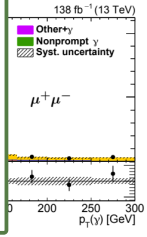












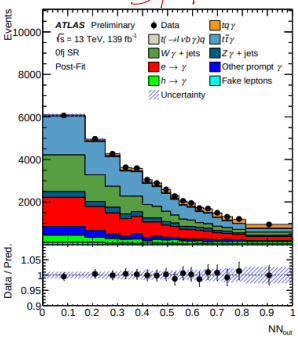
$t\gamma q$ Production

- Relevant to constraining non-resonant contributions of BSM, parametrized by EFT
- Two SR defined by: e/μ + γ + b-tag + 0/$\geq$ 1 forward jets
  - CR defined for $t\bar{t}\gamma$ and W+Jets
- NN implemented to separate signal from background in the 2 SR

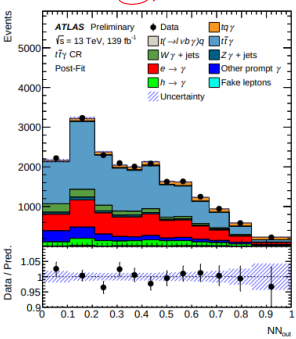
$$\sigma^{\text{Fid}}_{t\gamma q} = 580 \pm 19(\text{stat.}) \pm 63(\text{syst.})\ \text{fb}$$

$$\sigma^{\text{SM-Fid}}_{t\gamma q} \times \mathcal{B}r(t \to \ell\nu b) = 406^{+25}_{-32}(\text{scale} + \text{PDF})\ \text{fb}$$

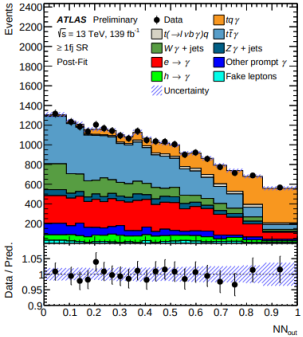
SR1



CR

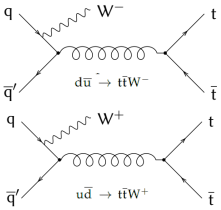


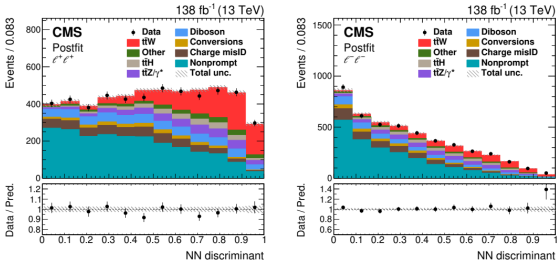
SR2

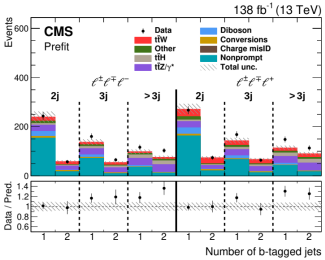


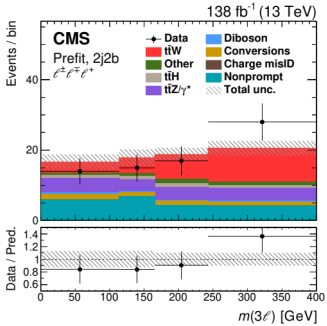
$t\bar{t}W$ Production

- Sizeble difference in $t\bar{t}W^+$ and $t\bar{t}W^-$: No gluon-gluon initial states
- Events with 2 or 3 ℓ + jets
- 2ℓ: NN classifier to distinguish $t\bar{t}W$ from $t\bar{t}Z$, $t\bar{t}H$, $t\bar{t}\gamma$ and nonprompt leptons
- 3ℓ: $m(3\ell)$ for (N_j, N_b) categories



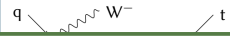


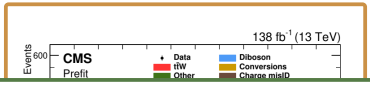


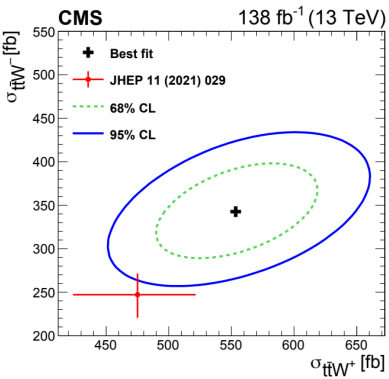


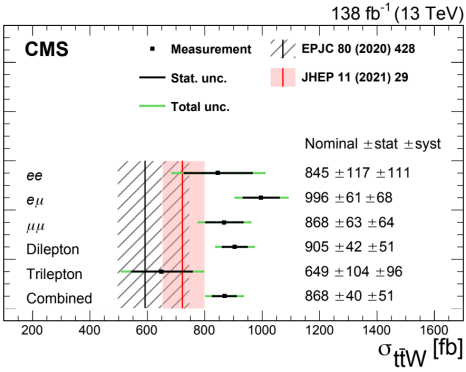
$t\bar{t}W$ Production

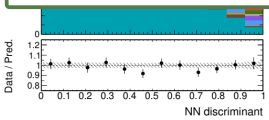
- Sizeble difference in $t\bar{t}W^+$ and $t\bar{t}W^-$. No gluon gluon initial

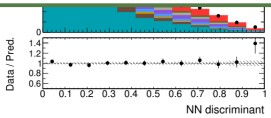


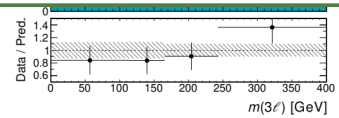




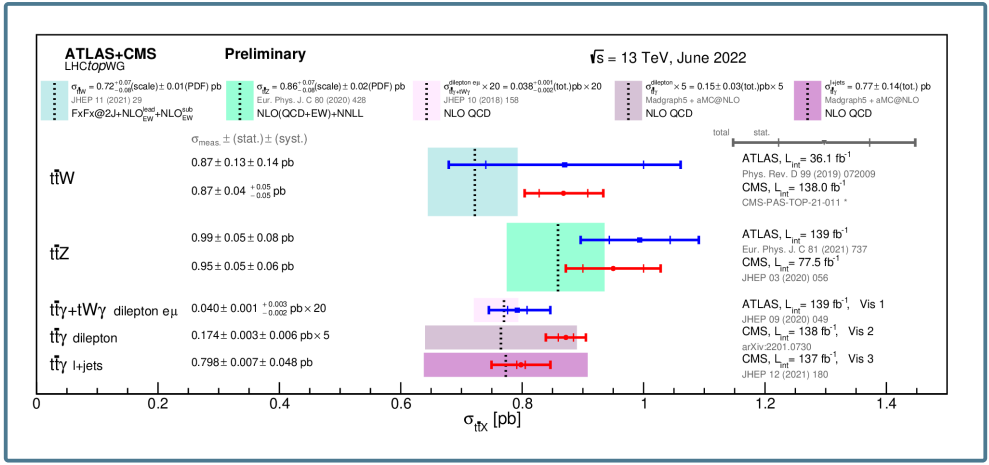




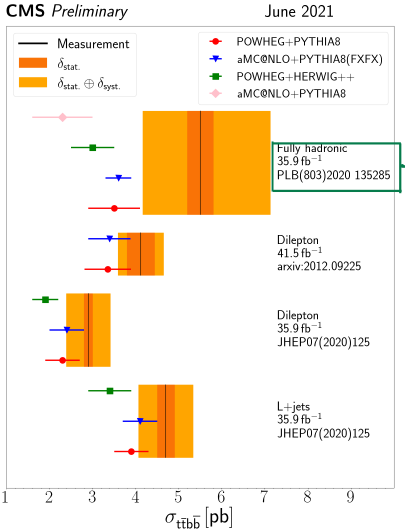


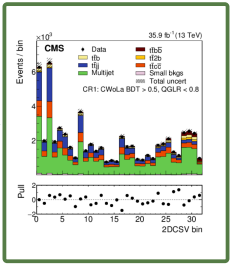


$t\bar{t}$V: Summary

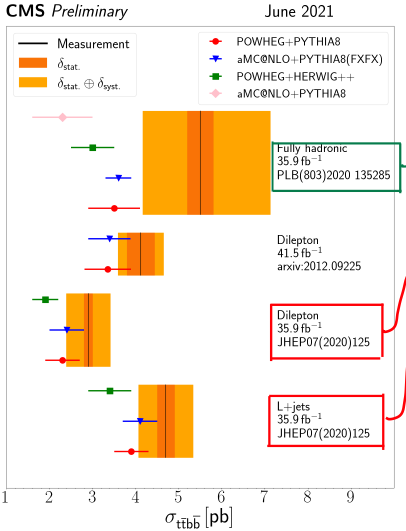


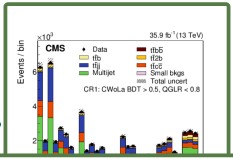
$t\bar{t}$HF Production

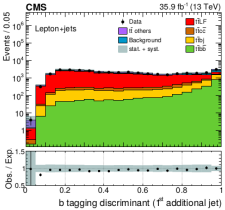


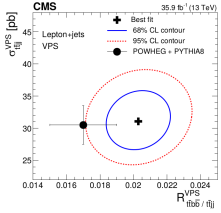


$t\bar{t}$HF Production

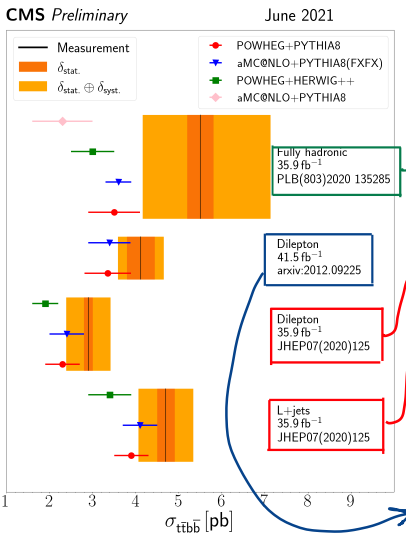


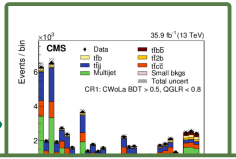


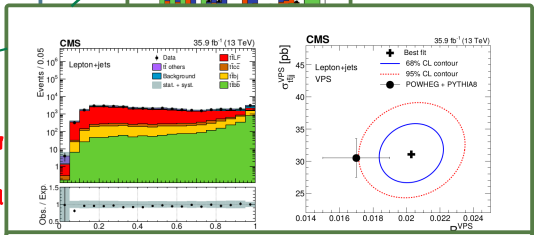


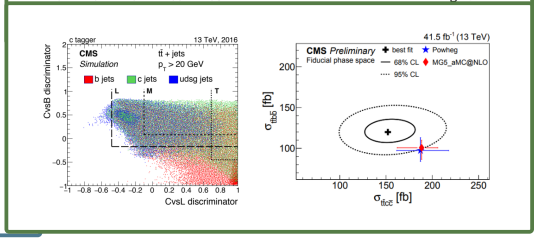


$t\bar{t}$HF Production









Summary

- ATLAS and CMS Collaborations has a strong program in the top-quark sector.
  - inclusive
  - differential 1D/2D/3D
  - exclusive
  - Different energies
  - pPb collisions
  - many more...
- Both collaborations are stil  everal analysis using the Run II.
- We are living our "Golden Years": Run-II is a window to a new precision era.
  - Top-quark studies are offering a different approach to searches of NP.
- Run III is here!!!! Exiting 13.6 TeV results are coming!
  - 15th International Workshop on Top-Quark Physics (TOP2022) is taking place right now... New results must be expected!!!
- New challenges in the reduction of the systematic uncertainties
- Many results from both collaborations did not fit in this presentation ($\mathrm{t\bar{t}t\bar{t}}$, $\mathrm{t\bar{t}Z}$...) but they are available on:
  - CMS Top-Quark Physics Results
  - ATLAS Top-Quark Physics Results

BACKUP