Top quark production, properties and rare processes

Physics in Collisions 2023, 10-13.10.2023
Arica, Chile,

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on behalf of the ATLAS and CMS collaborations

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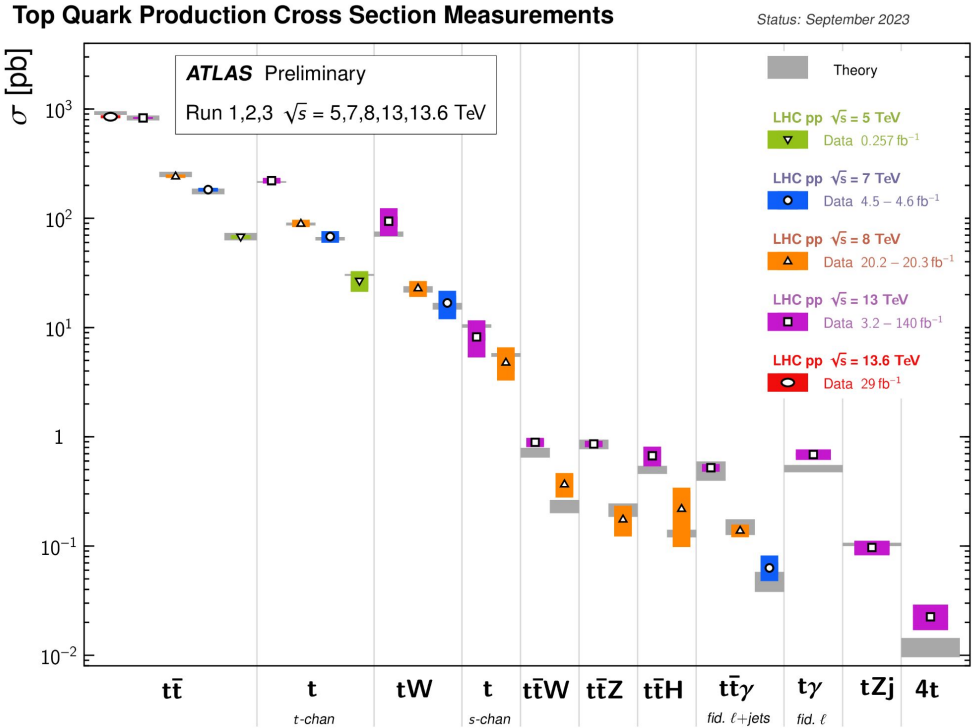
Top quark

- It was discovered at Tevatron in 1995
- **Mass of 173 GeV** → the heaviest elementary particle
- **Decay width of 1.33 GeV** → decays before hadronization → the only quark **appearing as a pseudo-bare quark** in experiments
- Excellent perturbative object - produced at small distances with effective α_s = 0.1 - good for precision QCD tests
- The top quark decays:
    - Leptonic (BR = 33 %)
    - Hadronic (BR = 67 %)

Top quark processes and their cross-sections

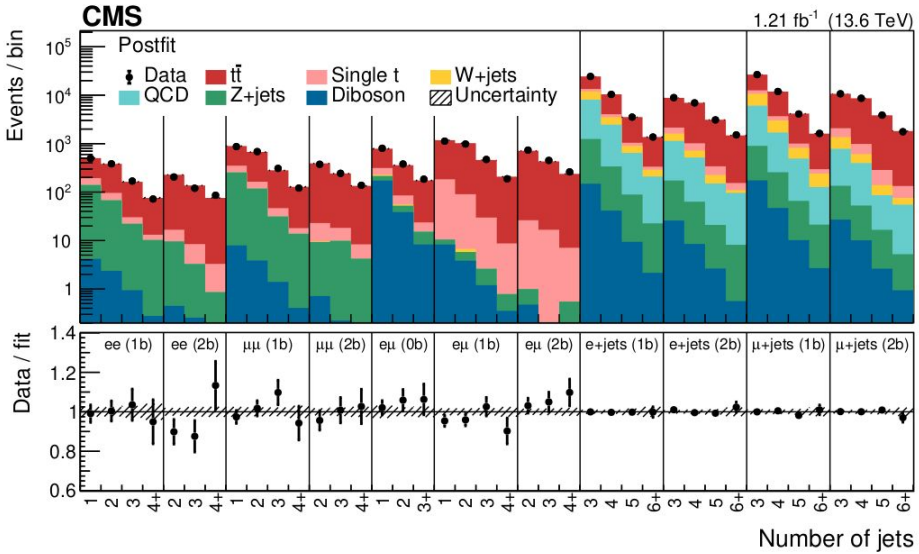
- The top quark production:
  - Pairs = $t\bar{t}$
  - Single-top = tq, tW …
  - Associated production with other particles (tX, $t\bar{t}$X, 3 tops, 4 tops …)
- Intensively studied by ATLAS and CMS experiments



[ATL-PHYS-PUB-2023-028]

Inclusive tt̄ cross-section at 13.6 TeV

- Published by CMS collaboration [JHEP 08 (2023) 204]
- Using 1.21 fb^{-1} of 13.6 TeV data, ℓ+jets and dilepton channels
- Using profile-likelihood fit on N_{jets} distribution in regions split by lepton flavor, number of leptons and number of b-jets
- Leading uncertainties: lepton ID, b-tagging and single-top modelling



ℓ+jets selection:
- $p_T^{\ell} > 35$ GeV
- At least 3 jets
- 1 or 2 b-jets

e^+e^- and $\mu^+\mu^-$ selection:
- $p_T^{\ell} > 35$ GeV
- $|m_{\ell\ell} - M_Z| > 15$ GeV
- $m_{\ell\ell} > 20$ GeV
- At least 1 b-jet

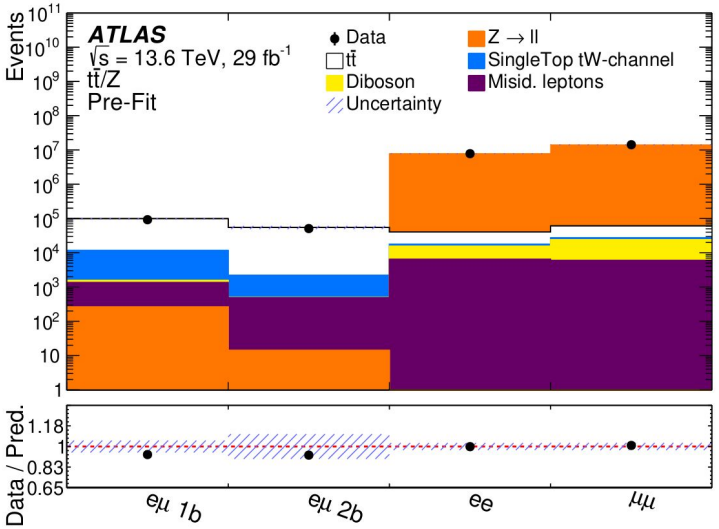
$e^{\pm}\mu^{\mp}$ selection:
- $p_T^{\ell} > 35$ GeV
- $|m_{\ell\ell} - M_Z| > 15$ GeV
- At least 1 jet

$$\sigma_{t\bar{t}}^{\text{measured}} = 881 \pm 23\,(\text{stat} + \text{syst}) \pm 20\,(\text{lumi})\,\text{pb}$$

$$\sigma_{t\bar{t}}^{\text{NNLO+NNLL}} = 924^{+32}_{-40}\,\text{pb}$$ [Phys. Rev. Lett. 110 (2013) 252004]

Measurement of $\sigma_{t\bar{t}}$ and $\sigma_{t\bar{t}}/\sigma_{Z+jets}$ ratio at 13.6 TeV

- Published by ATLAS collaboration [2308.09529v1]
- Using 29 fb^{-1} of 13.6 TeV dilepton data from 2022
- 1b and 2b regions fitted separately - able to fit b-jet reconstruction and tagging efficiency
- $\sigma_{t\bar{t}}$ and $R_{t\bar{t}/Z}$ extracted from the same profile-likelihood fit
- Leading uncertainties:
  - $t\bar{t}$ modelling
  - lepton reconstruction



Selection (emu regions for $t\bar{t}$):
- Exactly two leptons: $e^{\pm}\mu^{\mp}$
- One or two *b*-jets

Same-flavor selection (*Z*):
- Exactly 2 leptons: $e^{+}e^{-}$ or $\mu^{+}\mu^{-}$
- 66 GeV < m_{ll} < 116 GeV

Theory: [Phys. Rev. Lett. 110 (2013) 252004]

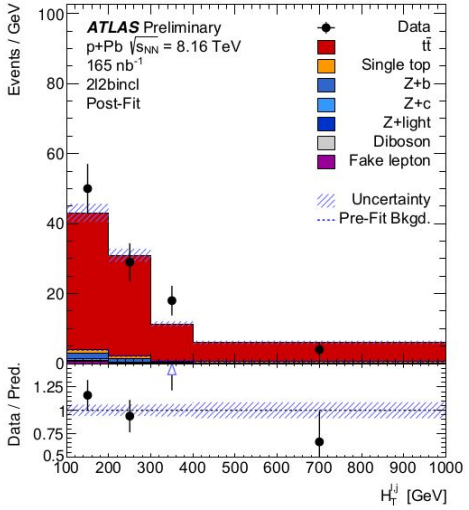
$$R^{\text{measured}}_{tt\bar{Z}} = 1.145 \pm 0.003\,(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002\,(\text{lumi}) \qquad R^{\text{theory}}_{tt\bar{Z}} = 1.238\,^{+0.063}_{-0.071}$$

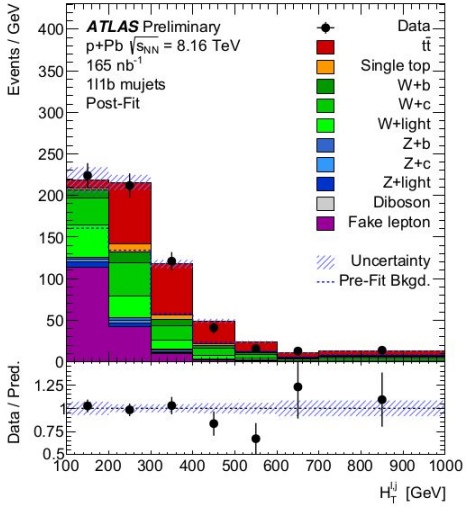
$$\sigma^{\text{measured}}_{t\bar{t}} = 850 \pm 3\,(\text{stat.}) \pm 18(\text{syst.}) \pm 20\,(\text{lumi})\,\text{pb} \qquad \sigma^{\text{NNLO+NNLL}}_{t\bar{t}} = 924^{+32}_{-40}\,\text{pb}$$

Observation of $t\bar{t}$ in p+Pb collisions at 8.16 TeV

- Using 165 nb^{-1} of p+Pb ATLAS data from 2016
- Dilepton and ℓ+jets channels have been used
- Dominant backgrounds: fakes, W+jets, single-top and Z+jets
- Fitting H_T in 6 analysis regions to get $\sigma_{t\bar{t}}$
  - **ℓ+jets regions:** e+jets 1b, μ+jets 1b, e+jets ≥2b, μ+jets ≥2b
  - **dilepton:** 1b and ≥2b
- Leading systematic uncertainties:
  - Jet energy scale
  - $t\bar{t}$ modelling
  - Fake leptons

[ATLAS-CONF-2023-063]





$$\sigma_{t\bar{t}} = 57.9 \pm 2.0\ (\text{stat.})\ ^{+4.9}_{-4.5}\ (\text{syst.})\ \text{nb} = 57.9\ ^{+5.3}_{-4.9}\ (\text{tot.})\ \text{nb}$$

Inclusive and differential $t\bar{t}$ cross-section at 13 TeV

- Published by ATLAS collaboration [JHEP07(2023)141]
- Measured in **dilepton *eμ* channel** in full Run 2 dataset
- Backgrounds relatively small: mostly single-top
- Luminosity uncertainty significantly reduced due to the new luminosity measurement: [2212.09379]
- Bin-by-bin unfolding is used to measure differential, fiducial and total x-sections (the last 2 have one true-level bin)
- Differential x-section measured in the following variables:

$$p_{\mathrm{T}}^{\ell},\ \left|\eta^{\ell}\right|,\ m^{e\mu},\ p_{\mathrm{T}}^{e\mu},\ \left|\eta^{e\mu}\right|,\ E^{e}+E^{\mu},\ p_{\mathrm{T}}^{e}+p_{\mathrm{T}}^{\mu}\ \text{and}\ \left|\Delta\Phi^{e\mu}\right|$$

- Four pairs used for double-differential:

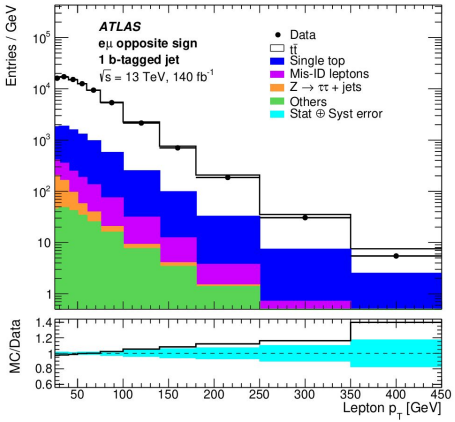
$$\left(\left|y^{e\mu}\right|,\ m^{e\mu}\right);\ \left(\left|\Delta\Phi^{e\mu}\right|,\ m^{e\mu}\right);\ \left(\left|\Delta\Phi^{e\mu}\right|,\ p_{\mathrm{T}}^{e\mu}\right);\ \left(\left|\Delta\Phi^{e\mu}\right|,\ E^{e}+E^{\mu}\right)$$

Selection:

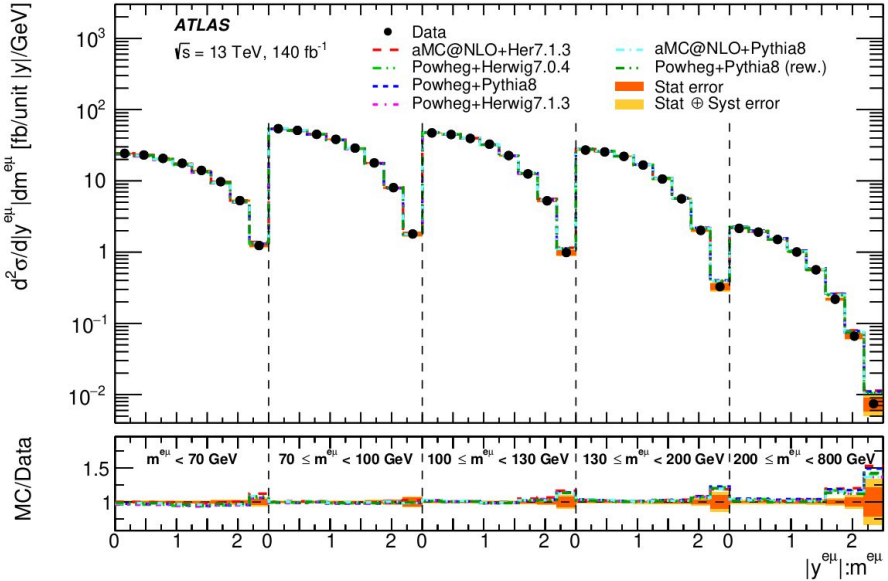
- Single-lepton trigger
- One electron and one muon
- One or two b-tagged jets
- $e^{\pm}\mu^{\mp}$ in signal regions
- $e^{\pm}\mu^{\pm}$ for DD fakes estimate

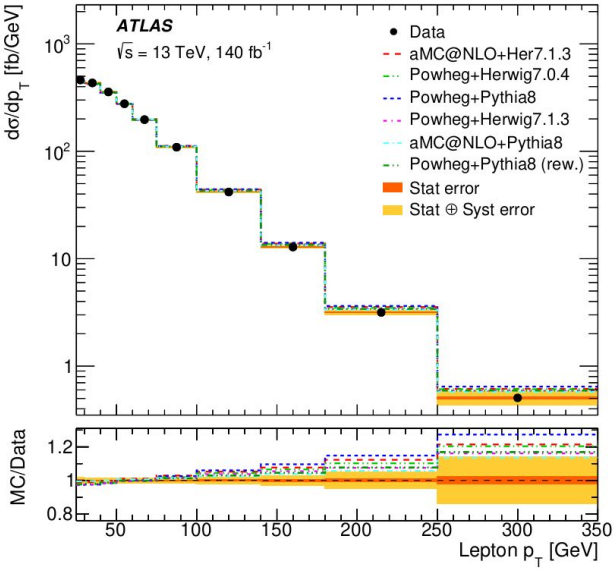
Fiducial volume (particle-level):

- $p_{\mathrm{T}}^{\ell} > 27$ (25) GeV for the leading (sub-leading) lep.
- $|\eta^{\ell}| < 2.5$



Inclusive and differential tt̄ cross-section at 13 TeV





The most precise inclusive measurement:

$$\sigma_{t\bar{t}}^{\text{measured}} = 829 \pm 1\,(\text{stat}) \pm 13\,(\text{syst}) \pm 8\,(\text{lumi}) \pm 2\,(\text{beam})\,\text{pb}$$

$$\sigma_{t\bar{t},\,\text{fid.}}^{\text{measured}} = 10.53 \pm 0.02\,(\text{stat}) \pm 0.13\,(\text{syst}) \pm 0.10\,(\text{lumi}) \pm 0.02\,(\text{beam})\,\text{pb}$$

$$\sigma_{tt,\,\bar{\text{fid.}}}^{\text{Powheg+Pythia8}} = 10.57\,\text{pb}$$

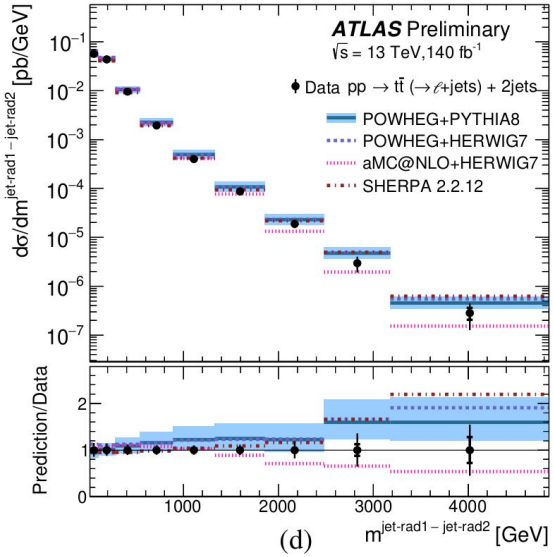
$$\sigma_{t\bar{t}}^{\text{NNLO+NNLL}} = 832^{+20}_{-29}(\text{scale}) \pm 23(m_t) \pm 35\,(\text{PDF} + \alpha_S)\,\text{pb}$$

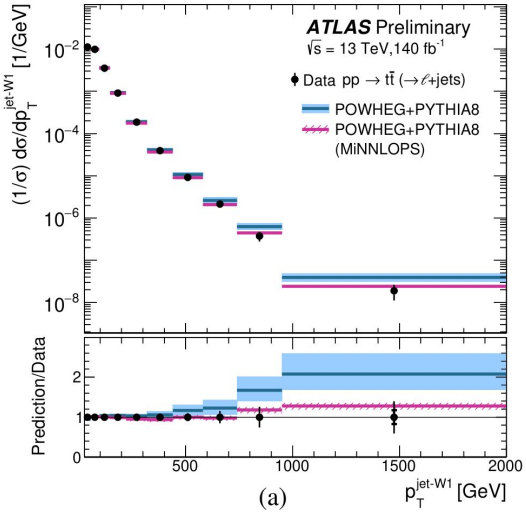
[Phys. Rev. Lett. 110 (2013) 252004]

Differential $t\bar{t}$ and $t\bar{t}$+jets cross-section in ℓ+jets

- Using full Run 2 ATLAS dataset, ℓ+jet channel [ATLAS-CONF-2023-068]
- Using events with 0, 1 or 2 additional jets, unfolding to particle level using Iterative Bayesian Unfolding
- First time using MiNNLOPS (better agreement with data)
- Measuring variables sensitive jet kinematics and topology:

$t\bar{t}$ inclusive	$t\bar{t}$+1jet channel	$t\bar{t}$+2jets channel
$p_{\mathrm{T}}^{\text{jet-W1}}$	$p_{\mathrm{T}}^{\text{jet-rad1}}$	$p_{\mathrm{T}}^{\text{jet-rad2}}$
$\lvert y^{\text{jet-W1}}\rvert$	$\lvert y^{\text{jet-rad1}}\rvert$	$\lvert y^{\text{jet-rad2}}\rvert$
$p_{\mathrm{T}}^{\text{jet-W2}}$	$\lvert\Delta\phi^{\text{toplep}-\text{jet-rad1}}\rvert$	$\lvert\Delta y^{\text{jet-rad1}-\text{jet-rad2}}\rvert$
$\lvert y^{\text{jet-W2}}\rvert$	$\lvert\Delta\phi^{\text{tophad}-\text{jet-rad1}}\rvert$	$\lvert\Delta\phi^{\text{jet-rad1}-\text{jet-rad2}}\rvert$
$\lvert\Delta y^{\text{jet-W1}-\text{jet-W2}}\rvert$	$\lvert\Delta\phi^{\text{jet-W1}-\text{jet-rad1}}\rvert$	$\lvert\Delta\phi^{\text{toplep}-\text{jet-rad2}}\rvert$
$\lvert\Delta\phi^{\text{jet-W1}-\text{jet-W2}}\rvert$	$m^{t\bar{t}}-\text{jet-rad1}$	$\lvert\Delta\phi^{\text{jet-W1}-\text{jet-rad2}}\rvert$
		$m^{\text{jet-rad1}-\text{jet-rad2}}$

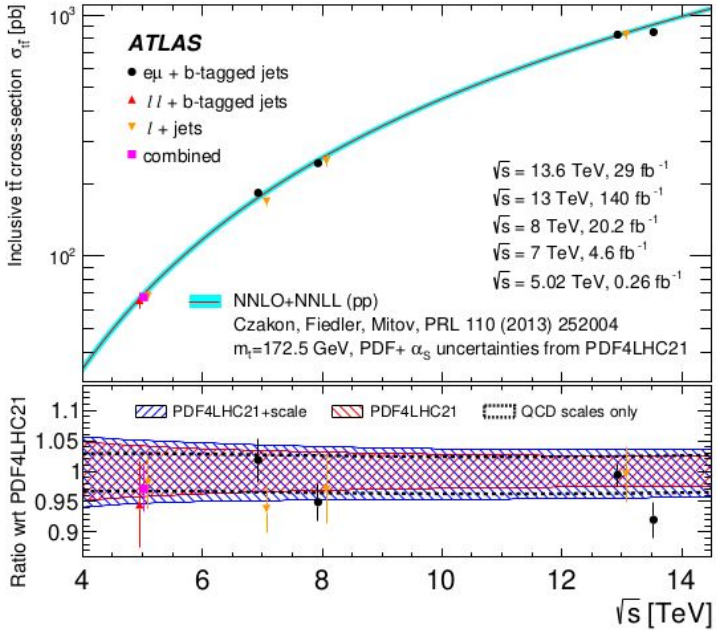


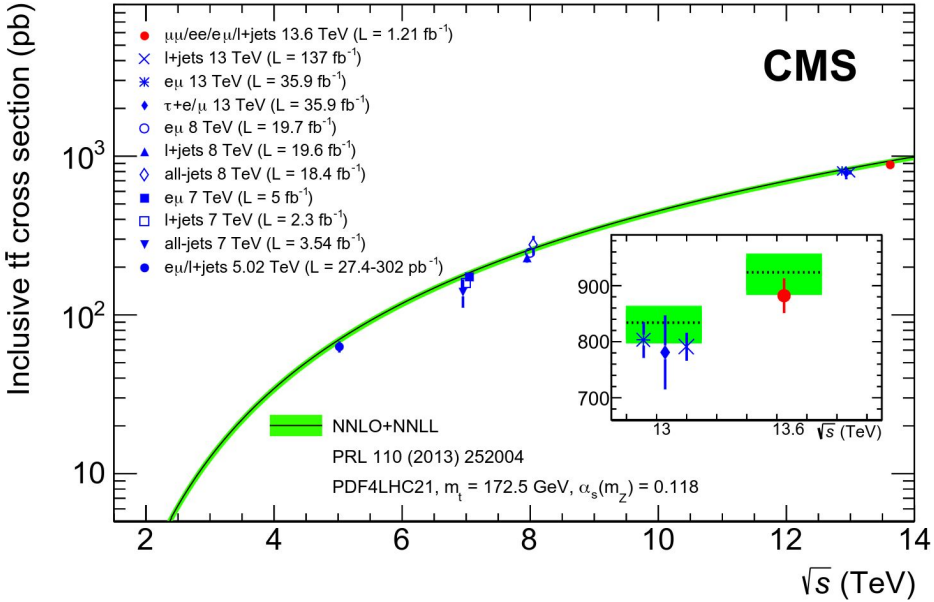


Leading systematic uncertainties:

- b-tagging
- Background modelling
- Statistical uncertainty

$t\bar{t}$ cross-section measurements - overview

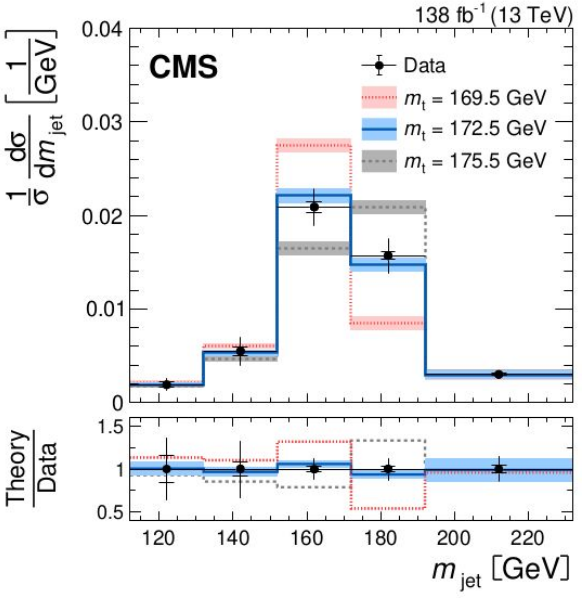




- Measured in *pp* collisions at energies ranging from 5 TeV to 13.6 TeV.
- Excellent agreement between the theory and experiment is observed!

Differential $t\bar{t}$ in m_j^{top} and the top-mass measurement

- Published by CMS collaboration [Eur. Phys. J. C 83 (2023) 560]
- Using **ℓ+jets** $t\bar{t}$ events with boosted top in full Run 2 dataset
- Leading backgrounds (below 10%): single-top and W+jets
- Improvement in systematics wrt. previous measurement by measuring jet mass scale in hadronic W-decays and measuring distribution of N(subjets) to control FSR systematics
- Using TUnfold [1205.6201] algorithm (least squares method) with Tikhonov (second discrete derivative) regularization



Fiducial volume:

- One lepton, $p_T^{\ell} > 60$ GeV
- $p_T^{\text{top-jet}} > 400$ GeV, all subjets $p_T > 30$ GeV & $|\eta|<2.5$
- $p_T^{\text{2nd jet}} > 10$ GeV
- $m^{\text{top-jet}} > m^{\ell + 2nd\ jet}$

Detector-level:

- Everything from fiducial
- At least one b-tag & $E_T^{miss} > 50$ GeV

Detector-level sideband region:

- $350\ \text{GeV} < p_T^{\text{top-jet}} > 400\ \text{GeV}$
- $55\ \text{GeV} < p_T^{\ell} < 60\ \text{GeV}$

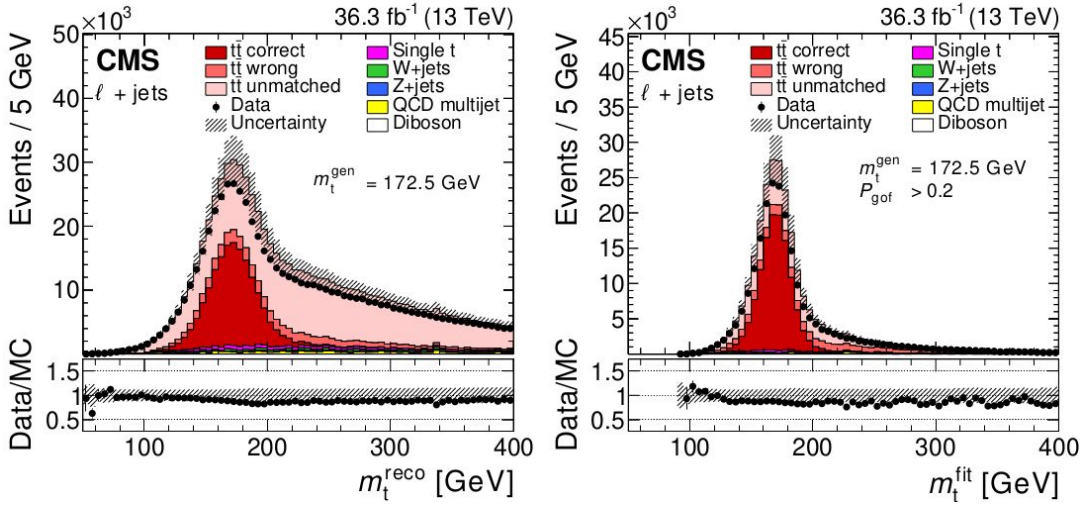
$$m_t = 173.06 \pm 0.24\,(\text{stat}) \pm 0.61\,(\text{exp}) \pm 0.47\,(\text{model}) \pm 0.23\,(\text{theo})\ \text{GeV} = 173.06 \pm 0.84\ \text{GeV}$$

Top mass at 13 TeV in $t\bar{t} \rightarrow \ell$+jets events

- By CMS with 2016 (36.3 fb^{-1}) **ℓ+jets** data [2302.01967v1]
- Kinematic fit used to assign jets to parton and extract m_t. Three possible cases in simulation: correct, wrong, unmatched
- χ^2 and P_{gof} from fit used to define two regions: $P_{gof} < 0.2$ and $P_{gof} > 0.2$
- 5 variables used in the profile-likelihood fit to extract m_t and constrain systematics:

Selection:
- Exactly one lepton
- At least 4 jets, exactly two of them b-tagged

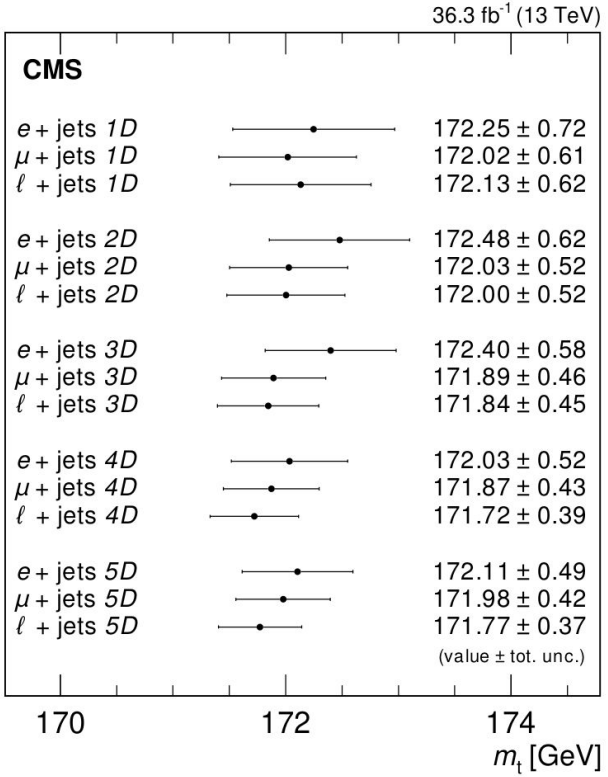
Histogram Observable	Category	Set label 1D	2D	3D	4D	5D
m_t^{fit}	$P_{gof} > 0.2$	×	×	×	×	×
m_W^{reco}	$P_{gof} > 0.2$		×	×	×	×
$m_{\ell b}^{reco}$	$P_{gof} < 0.2$			×	×	×
$m_{\ell b}^{reco} / m_t^{fit}$	$P_{gof} > 0.2$				×	×
$R_{bq}^{reco} = \frac{p_T^{b1} + p_T^{b2}}{p_T^{q1} + p_T^{q2}}$	$P_{gof} > 0.2$					×



Top mass at 13 TeV in $t\bar{t} \rightarrow \ell$+jets events

- Events split based on lepton flavor.
- Leading uncertainties:
  - Jet energy correction
  - Final state radiation modelling
  - Color reconnection modelling

$$m_t^{5D} = 171.77 \pm 0.37\,\text{GeV}$$

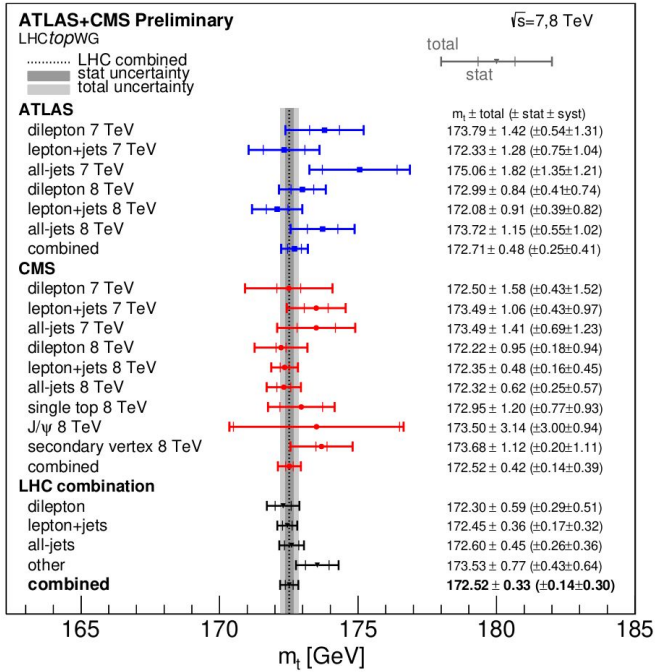


Top mass LHC combination (7 and 8 TeV)

ATLAS-CONF-2023-066

- Combining ATLAS and CMS data from 7 and 8 TeV
- All three decay channels (all-hadronic, ℓ+jets and dilepton) have been used
- BLUE method used to combine the measurements, $m_t = \sum_i w^i m_t^i$, optimal $w^i \rightarrow$ minimal uncertainty
- No statistical overlap between measurements
- 3 possibilities for systematic correlations: strong (ρ=0.85), partial (ρ=0.5), uncorrelated
- Leading systematic uncertainties:

Uncertainty category	Uncertainty impact [GeV]		
	LHC	ATLAS	CMS
LHC b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
LHC JES 1	0.08	0.18	0.06

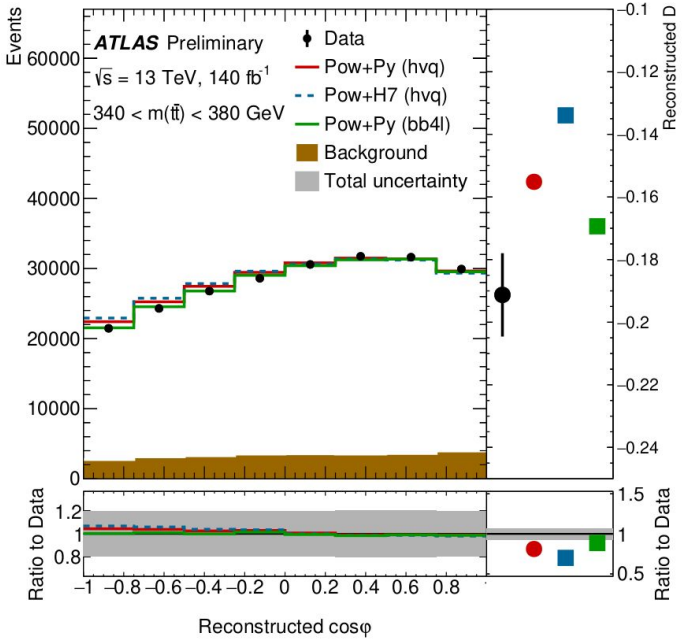


$$m_t = 172.52 \pm 0.14\,(\text{stat}) \pm 0.30\,(\text{syst})\,\text{GeV} = 172.52 \pm 0.33\,\text{GeV}$$

Quantum entanglement in $t\bar{t}$ production

ATLAS-CONF-2023-069

- Published by ATLAS with full Run 2 ***eμ*** data
- First $t\bar{t}$ entanglement observation [CERNCOURIER]
- Entangled particles = state of one cannot be described independently of the other
- Quantum entanglement in $t\bar{t}$ events → correlations between spin of the top-quarks → can be observed in angles between decay products
- φ = leptons are boosted to (anti-)top rest frame and the angle between them is calculated



$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

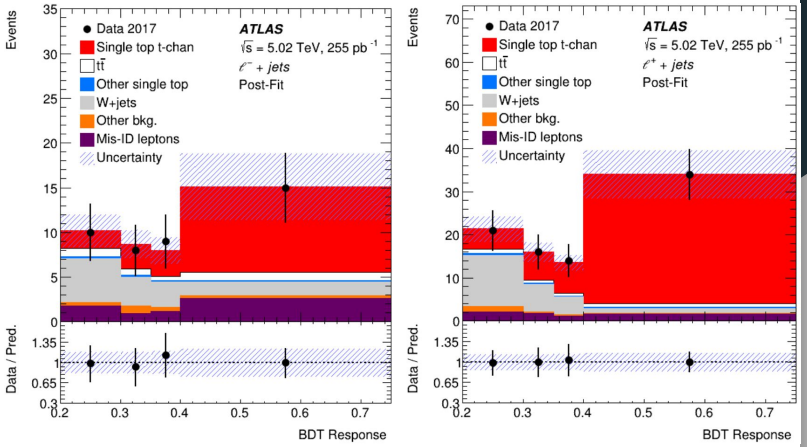
$$D = -3\cdot\langle\cos\varphi\rangle = \mathrm{tr}[\mathbf{C}]/3$$

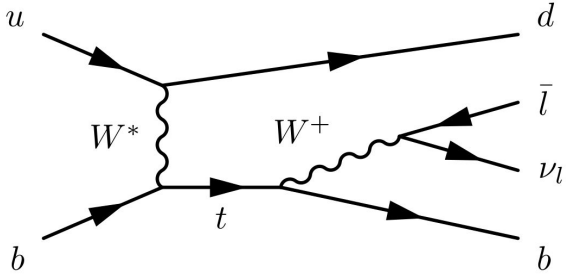
$$D = -0.547 \pm 0.002\ (\mathrm{stat.}) \pm 0.021\ (\mathrm{syst.})\ \text{for}\ 340 < m_{t\bar{t}} < 380\ \mathrm{GeV}$$

Dominant uncertainty: **signal modelling**

Single top t-channel cross-section measurement

- Using 255 pb^{-1} of 5.02 TeV *pp* ATLAS data [2310.01518]
- Cross-section sensitive to V_{tb}
- BDT trained to separate signal from backgrounds (mostly W+jets and fake leptons)
- Extracting **$\sigma(tq+\bar{t}q)$** and **$R_t = \sigma(tq)/\sigma(\bar{t}q)$** from profile likelihood fit of the BDT output distribution in 2 regions split by lepton charge: ℓ^-+jets and ℓ^++jets





$$\sigma^{\text{measured}}_{tq+\bar{t}q} = 27.1\,^{+4.4}_{-4.1}(\text{stat.})\,^{+4.4}_{-3.7}(\text{syst.})\ \text{pb}$$

$$R^{\text{measured}}_{T} = 2.73\,^{+1.43}_{-0.82}(\text{stat.})\,^{+1.01}_{-0.29}(\text{syst.})$$

Dominant syst. uncertainties:

- MC stat. uncertainty
- Signal modelling:
  - Matrix element
  - Parton showering
- Fake lepton modelling

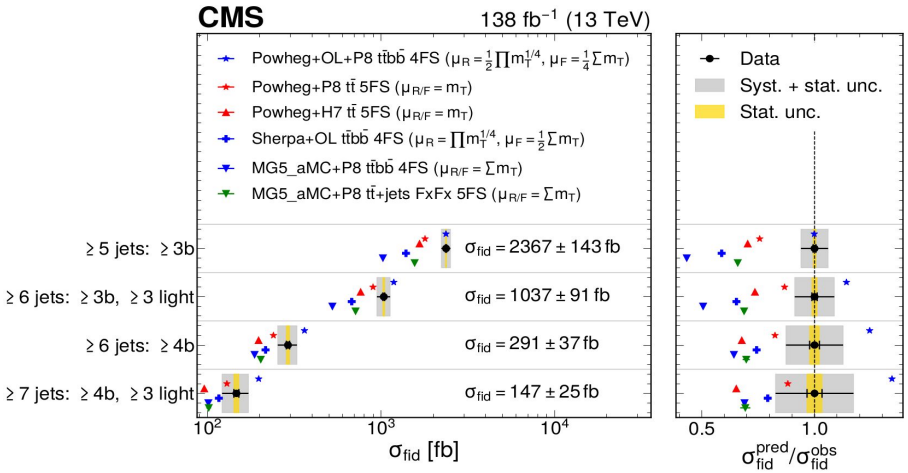
Selection:

- Exactly one lepton (electron or muon)
- Exactly 2 jets, exactly 1 of them b-tagged
- $1.5 < |\eta^{\text{ligth-jet}}| < 4.0$ & $|\eta^{\text{ligth-jet}} - \eta^{\text{b-jet}}| > 1.5$
- $m_T^W > 35$ GeV & $E_T^{\text{miss}} > 15$ GeV
- $E_T^{\text{miss}} + m_T^W > 70$ GeV
- $H_T > 185$ GeV
- $m(\ell,\text{b-jet}) < 165$ GeV & $M^W < 102$ GeV
- 140 GeV $< m^{\text{top}} < 225$ GeV

Inclusive and differential cross section of ttbb by CMS

- Published by CMS with full Run 2 **ℓ+jets** data [2309.14442]
- Leading backgrounds: *tt̄+cc, tt̄+light*
- **Inclusive x-section:** profile-likelihood fit on the region-specific variable: $|\eta(b_3)|$ in 5j3b, H_T^{light} in 6j3b3l, $|\eta(b_2^{extra})|$ in 6j4b and $|\Delta\phi(lj_1^{extra}, b_{soft})|$ in 7j4b3l

Leading systematics:
- b-tagging
- Renormalization scale:
  - *tt̄*+bb
  - *tt̄*+b
  - *tt̄*



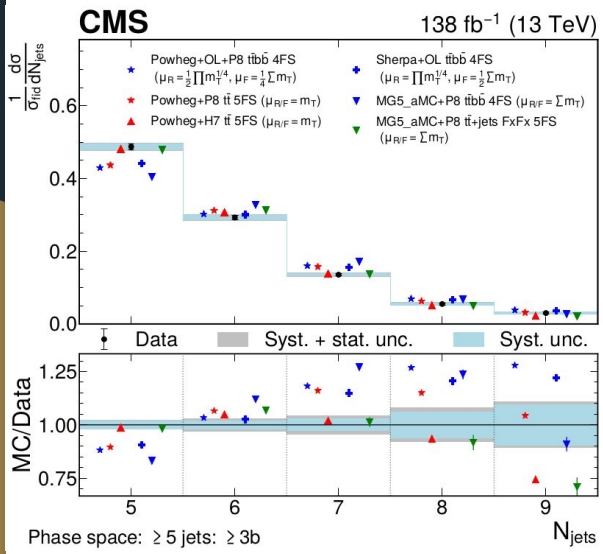
Selection (SR):
- Exactly one lepton
- At least 5 jets
- $\sum p_T^{jet} > 150$ GeV
- At least 3 medium (75-80% WP) b-tags

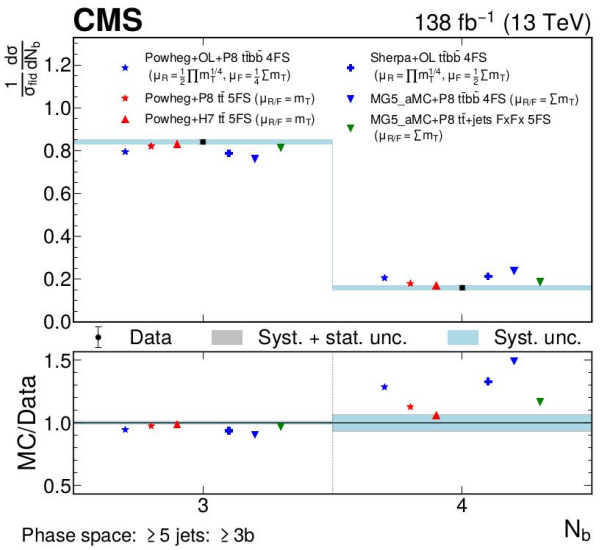
Split into 4 (overlapping) signal regions (detector and particle):
- 5j3b (≥5j & ≥3b)
- 6j4b (≥6j & ≥4b)
- 6j3b3l (≥6j & ≥3b & ≥3l)
- 7j4b3l (≥7j & ≥4b & ≥3l)

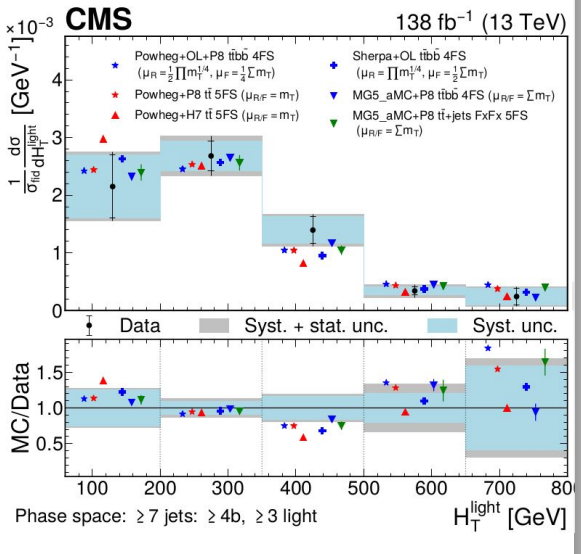
j = jet of any type
b = medium b-jets
l = light jet

Inclusive and differential cross section of $t\bar{t}bb$ by CMS

- Unfolding to particle-level using maximum likelihood unfolding
- Differential cross-section measured in 29 observables, such as number of jets, b-jets, kinematics of the b-jets, H_T^b, H_T^j, m_{bb}^{max}, ΔR_{bb}^{avg} …

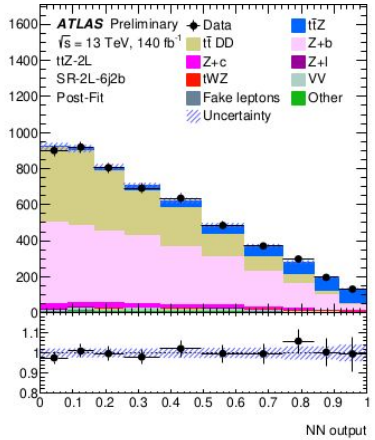




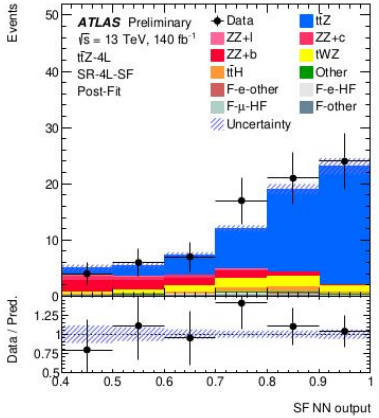


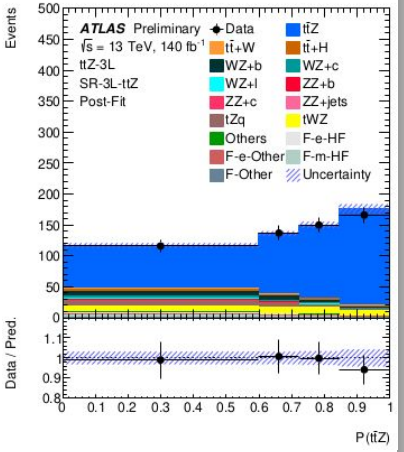
Differential and inclusive ttZ measurement

- Refined measurement with full Run 2 data by ATLAS [ATLAS-CONF-2023-065]
- Using profile-likelihood fit in 2ℓ, 3ℓ and 4ℓ channels for inclusive measurement
- Profile-likelihood unfolding in 3ℓ and 4ℓ for differential measurement
- Spin correlations observed with 1.8σ significance.
- EFT interpretation + spin correlations measurement
- Using DNN in all channels for signal vs. background separation, defining signal regions based on its output



- Three regions per channel, fitting DNN output distribution in most of the regions (using yields and b-tagging working point in some regions)
- Leading uncertainties: background normalizations, lepton and jet related uncertainties





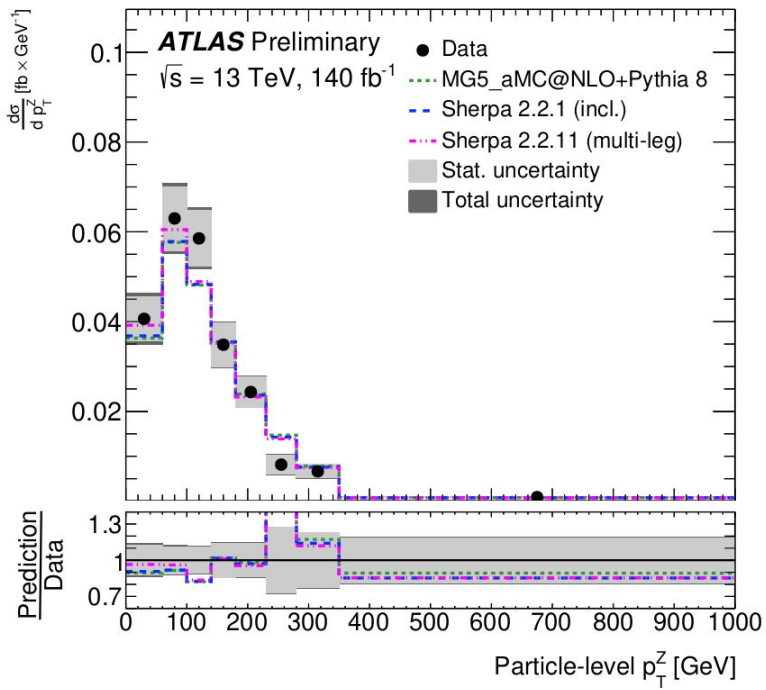
$$\sigma_{t\bar{t}Z}^{\text{measured}} = 0.86 \pm 0.06\,\text{pb} = 0.086 \pm 0.04\,(\text{stat}) \pm 0.04\,(\text{syst})\,\text{pb}$$

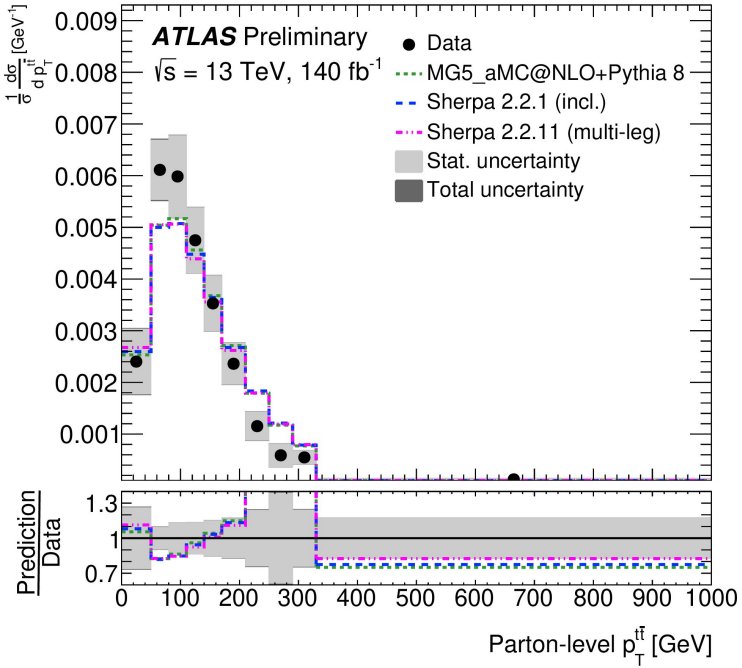
$$\sigma_{t\bar{t}Z}^{\text{NLO+NNLL}} = 0.863\,^{+0.073}_{-0.085}\,(\text{scale}) \pm 0.028\,(\text{PDF} \oplus \alpha_s)\,\text{pb}$$ [Eur. Phys. J. C 79 (2019) 249]

Differential and inclusive ttZ measurement

- Unfolding 9 variables in 3ℓ+4ℓ combination, 5 in 3ℓ and 3 in 4ℓ.

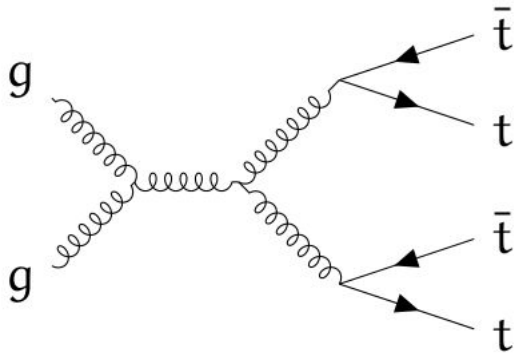
	Variable
3ℓ + 4ℓ	p_{T}^{Z}
	$\lvert y^{Z}\rvert$
	$\cos\theta_{Z}^{*}$
	p_{T}^{t}
	$p_{\mathrm{T}}^{t\bar{t}}$
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$
	$m^{t\bar{t}Z}$
	$m^{t\bar{t}}$
	$\lvert y^{t\bar{t}Z}\rvert$
3ℓ	H_{T}^{ℓ}
	$\lvert\Delta\phi(Z, t_{\mathrm{lep}})\rvert$
	$\lvert\Delta y(Z, t_{\mathrm{lep}})\rvert$
	$p_{\mathrm{T}}^{\ell,\mathrm{non-}Z}$
	N_{jets}
4ℓ	H_{T}^{ℓ}
	$\lvert\Delta\phi(\ell_{t}^{+}, \ell_{\bar{t}}^{-})\rvert$
	N_{jets}

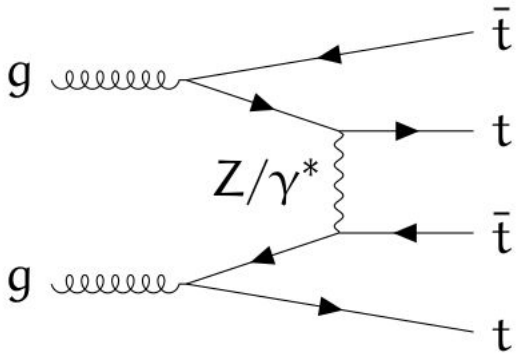


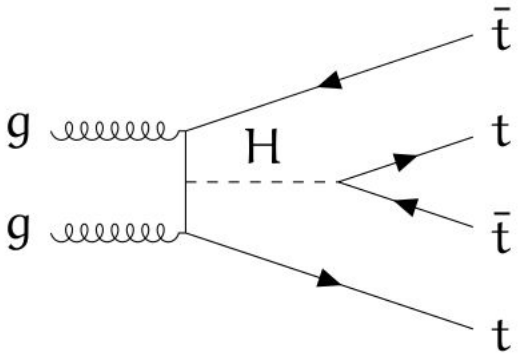


Four tops production

- Recently observed by both ATLAS [EPJC 83 (2023) 496] and CMS [2305.13439v1]
- Cross-section sensitive to top-quark Yukawa coupling, can be modified by BSM physics such as gluino pair production, heavy scalar boson + top production etc.
- Rare process in SM: $\sigma_{t\bar{t}t\bar{t}}^{\mathrm{NLO(QCD+EW)+NLL'}} = 13.37(2)\,^{+1.04}_{-1.78}$ fb at 13 TeV [2212.03259]
- Leading background processes: *ttW* and fake leptons
- Up to 4 leptons seen in detector

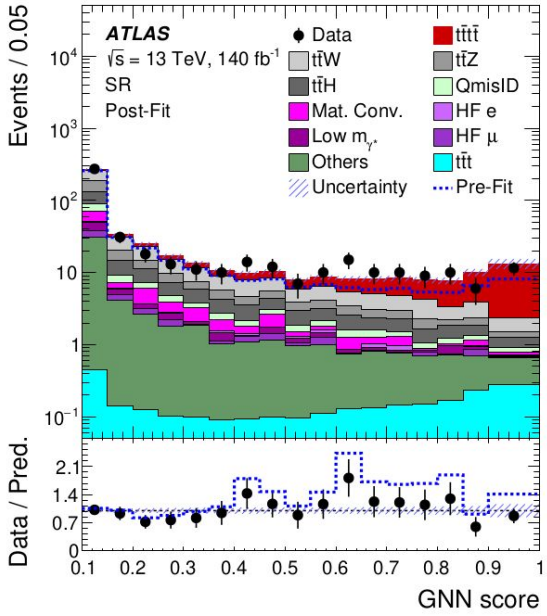






Four tops observation at 13 TeV by ATLAS

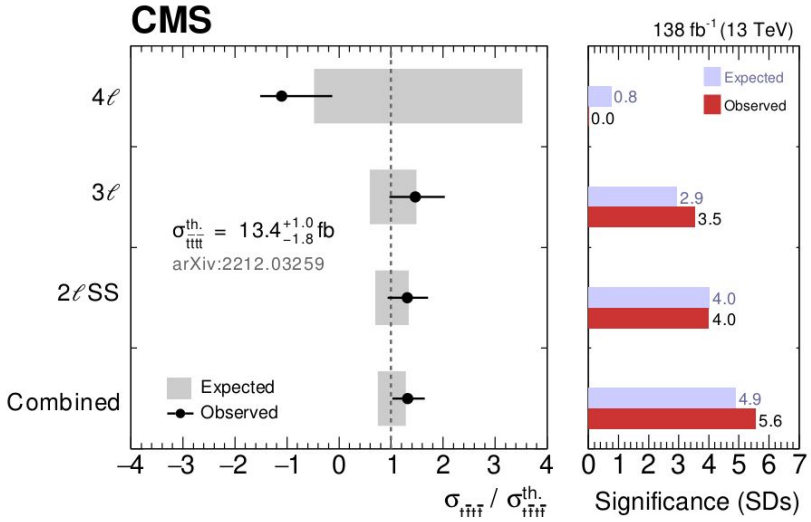
- Using 2ℓ SS, 3ℓ and 4ℓ channels with the full Run 2 dataset
- Graph Neural Network used to separate signal from backgrounds (mostly $t\bar{t}+X$)
- Profile likelihood fit is used to extract $\sigma_{t\bar{t}t\bar{t}}$ from distributions of GNN discriminant
- Normalizations of 4 fake-lepton background components, $t\bar{t}W^+$ and $t\bar{t}W^-$ are free floating and fitted simultaneously with the signal cross section
- Leading systematic uncertainties:
  - $t\bar{t}t\bar{t}$ modelling (matrix element and parton showering)
  - b-tagging and jet-related uncertainties
  - $t\bar{t}H$ modelling and $t\bar{t}W$ modelling
- **6.1σ significance** wrt. null hypothesis



$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\ \text{fb} = 22.5\,^{+6.6}_{-5.5}\ \text{fb}$$

Four tops observation at 13 TeV by CMS

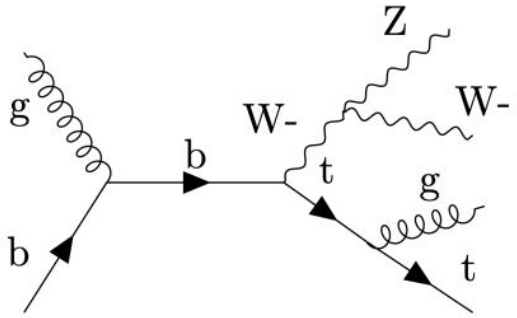
- Using 2ℓ SS, 3ℓ and 4ℓ channels with the full Run 2 dataset
- BDT used to separate signal from backgrounds (mostly $t\bar{t}+X$)
- Using profile likelihood fit: free floating signal strength, $t\bar{t}W$ and $t\bar{t}Z$ normalizations
- Fitting BDT output in signal regions. In control regions fitting N_{jets} and sum of lepton charges
- Leading systematic uncertainties:
  - $t\bar{t}t\bar{t}$ modelling (matrix element and parton showering)
  - DEEPJET correction factors and JES
  - Additional b-jets and jets modelling in $t\bar{t}W$
- **5.6σ significance** wrt. null hypothesis

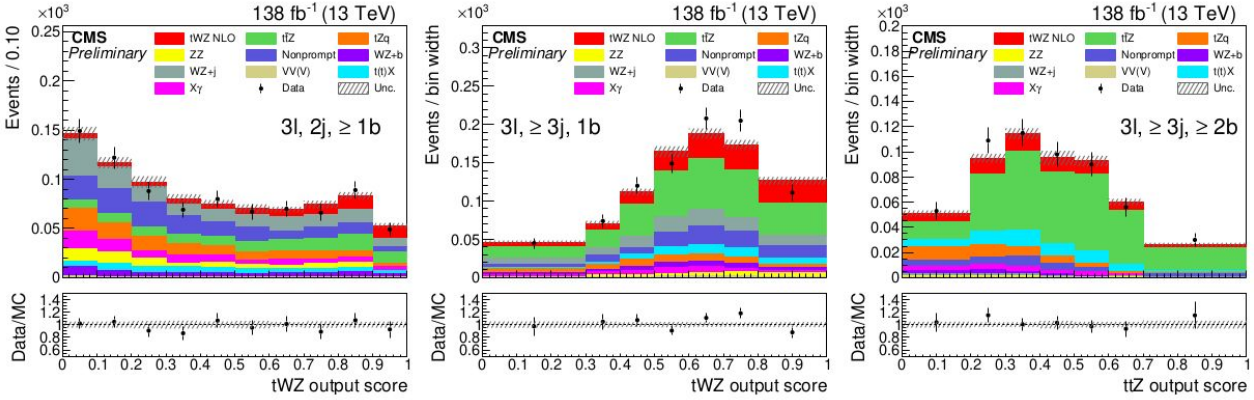


$$\sigma(\mathrm{t\bar{t}t\bar{t}}) = 17.7\,^{+3.7}_{-3.5}\,(\mathrm{stat})\,^{+2.3}_{-1.9}\,(\mathrm{syst})\,\mathrm{fb} = 17.7\,^{+4.4}_{-4.0}\,\mathrm{fb}$$

Evidence of tWZ production at 13 TeV by CMS

- Using full Run II data [CMS-TOP-22-008]
- Targeting decays W→ℓν, Z→ℓℓ, t →anything (3 or 4 leptons)
- 5 SRs: 3 low p_T: $SR_{3l,3j}$, $SR_{3l,2j}$ and SR_{4l} and 2 boosted: $SR_{had}^{Boosted}$,$SR_{lep}^{Boosted}$
- DNN used to suppress (mostly *tt̄Z*) background in low-p_T SRs
- Leading systematic uncertaintv: *tt̄Z* normalization
- Profile-likelihood fit of DNN output (low-p_T regions) and event yields (boosted regions)





Significance: 3.5σ

$$\sigma_{tWZ}^{\text{measured}} = 0.37 \pm 0.05\,(\text{stat}) \pm 0.10\,(\text{syst})\,\text{pb}$$

Conclusions

- A lot of top-related measurements were published during the last year by both ATLAS and CMS collaborations
- The ***tt̄* production cross section** has been already measured **at 13.6 TeV** by both ATLAS and CMS. Good agreement with the theory is seen
- **Multiple differential and inclusive *tt̄*** cross-section measurements have been published
- Production of the **4 top-quarks** (very rare SM process) has been observed by both ATLAS and CMS
- Multiple measurements of the top quark produced with other particles (**top +X**, X=vector boson or $b\bar{b}$ pair) have been performed.
- Multiple measurements of the **top-quark mass** have been presented
- **Single-top** production was observed **at 5.02 TeV**
- **Quantum entanglement** in $t\bar{t}$ production was observed at 13 TeV

Back-up slides

Top quark related measurements in the last year

Title	Link	Collab.
First measurement of the top quark pair production cross section in proton-proton collisions at √s = 13.6 TeV	HEP 08 (2023) 204	CMS
Measurement of the top quark mass using a profile likelihood approach with the lepton+jets final states in proton-proton collisions at √s = 13 TeV	2302.01967v1	CMS
Measurement of the differential tt production cross section as a function of the jet mass and extraction of the top quark mass in hadronic decays of boosted top quarks	Eur. Phys. J. C 83 (2023) 560	CMS
Inclusive and differential cross section measurements of $t\bar{t}bb$ production in the lepton+jets channel at √s= 13 TeV with the CMS detector	2309.14442	CMS
Evidence for tWZ production in proton-proton collisions at √s= 13 TeV in multilepton final states	CMS-TOP-22-008	CMS
Observation of four top quark production in proton-proton collisions at √s = 13 TeV	2305.13439v1	CMS

Top quark related measurements in the last year

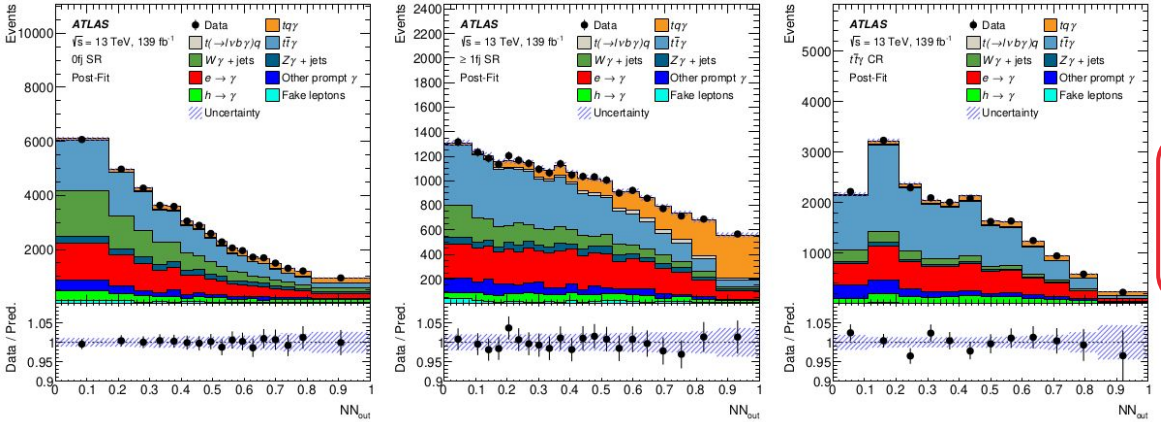
Title	Link	Collab.
Observation of four-top-quark production in the multilepton final state with the ATLAS detector	EPJC 83 (2023) 496	ATLAS
Measurement of the inclusive $t\bar{t}$ production cross section in the lepton+jets channel in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector using support vector machines	Phys. Rev. D 108 (2023) 032014	ATLAS
Measurement of the charge asymmetry in top-quark pair production in association with a photon with the ATLAS experiment	Phys. Lett. B 843 (2023) 137848	ATLAS
Observation of single-top-quark production in association with a photon using the ATLAS detector	2302.01283v1	ATLAS
Inclusive and differential cross-sections for dilepton $t\bar{t}$ production measured in $\sqrt{s}$ = 13 TeV *pp* collisions with the ATLAS detector	JHEP07(2023)141	ATLAS
Measurement of the $t\bar{t}$ cross section and its ratio to the *Z* production cross section using *pp* collisions at $\sqrt{s}$ = 13.6 TeV with the ATLAS detector	2308.09529v1	ATLAS
Measurement of the total and differential cross-sections of $t\bar{t}W$ production in *pp* collisions at 13 TeV with the ATLAS detector	ATLAS-CONF-2023-019	ATLAS
Search for leptonic charge asymmetry in $t\bar{t}W$ production in final states with three leptons at $\sqrt{s}$ =13 TeV	JHEP 07 (2023) 033	ATLAS
Measurement of jet substructure in boosted $t\bar{t}$ events with the ATLAS detector using 140 fb^{-1} of 13 TeV *pp* collisions	ATLAS-CONF-2023-027	ATLAS
Measurement of t-channel single-top-quark production in pp collisions at $\sqrt{s}$=5.02 TeV with the ATLAS detector	2310.01518	ATLAS

Another very recent (last month) top-quark related results

Title	Link	Collab.
Combination of measurements of the top quark mass from data collected by the ATLAS and CMS experiments at $\sqrt{s}$ = 7 and 8 TeV	ATLAS-CONF-2023-066	ATLAS+CMS
Observation of quantum entanglement in top-quark pair production using *pp* collisions of $\sqrt{s}$ = 13 TeV with the ATLAS detector	ATLAS-CONF-2023-069	ATLAS
Measurement of differential cross sections in $t\bar{t}$ and $t\bar{t}$+jets production in the lepton+jets decay mode in pp collisions at $\sqrt{s}$ = 13 TeV using 140 fb^{-1} of ATLAS data	ATLAS-CONF-2023-068	ATLAS
Observation of $t\bar{t}$ production in lepton+jets and dilepton channels in p+Pb collisions at $\sqrt{s}$ NN = 8.16 TeV with the ATLAS detector	ATLAS-CONF-2023-063	ATLAS
Inclusive and differential cross section measurements of ttZ production in *pp* $\sqrt{s}$ = 13 TeV with the ATLAS detector, including EFT and spin correlations	ATLAS-CONF-2023-065	ATLAS

Observation of tqγ by ATLAS

- Published by ATLAS with full Run II data [2302.01283v1]
- Only radiative photon production considered as the signal
- Leading backgrounds: $t\bar{t}\gamma$ and Wγ
- Two NNs trained (one in =0 fj SR, one in ≥1 fj SR) to separate signal from background
- NN output used in profile-likelihood fit, with free floating $t\bar{t}\gamma$ and Wγ normalizations



Selection (SR):

- Exactly one lepton
- Exactly one tight b-jet, no additional loose b-jet
- At least one photon
- E_T^{miss} > 30 GeV

2 signal regions:

- No forward jet (fj)
- ≥1 forward jet

***tt̄γ* control region:**

- Additional b-jet

***Wγ* control region:**

- Similar to SR, but different b-tagging requirements

9.3σ significance

$$\sigma_{t\gamma}^{\text{measured}} = 688 \pm 23\,(\text{stat})\,^{+75}_{-71}\,(\text{syst})\ \text{fb}$$

$$\sigma_{t\gamma}^{\text{theory, NLO}} = 515\,^{+36}_{-42}\ \text{fb}$$

Charge asymmetry in $t\bar{t}\gamma$ at 13 TeV

- Published by ATLAS with full Run II data [Phys. Lett. B 843 (2023) 137848]
- Larger qq/gg fraction compared to $t\bar{t}$ -> higher asymmetry
- Due to QED ISR and FSR interference, top-quarks are produced more likely in the original anti-quark direction resulting in:
  - Forward-backward asymmetry in $p\bar{p}$ collisions
  - Central-forward asymmetry in pp collisions

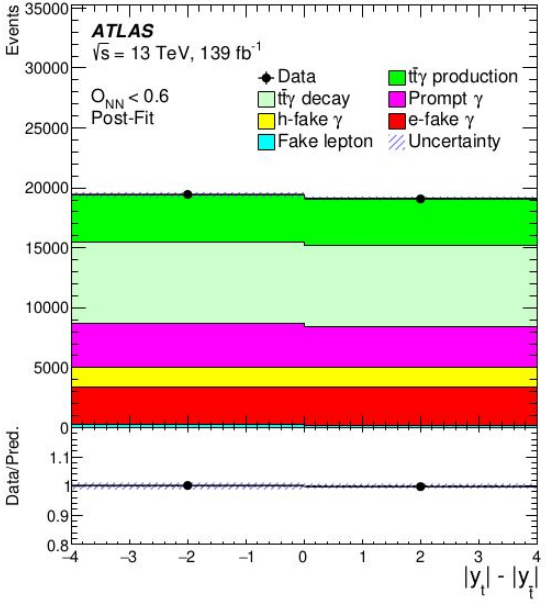
$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

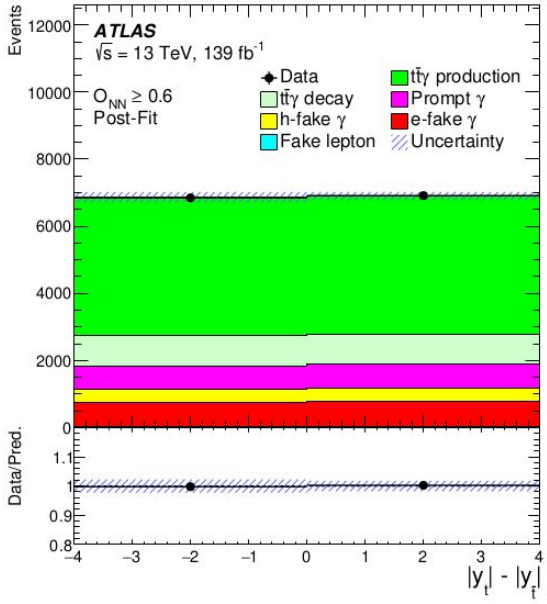
Selection:
- Exactly one lepton
- Exactly one photon
- At least 4 jets, at least one of them b-tagged
- $\Delta R(\ell,\gamma) > 0.4$
- $|M_{\ell\gamma} - M_Z| > 5$ GeV (for electrons)

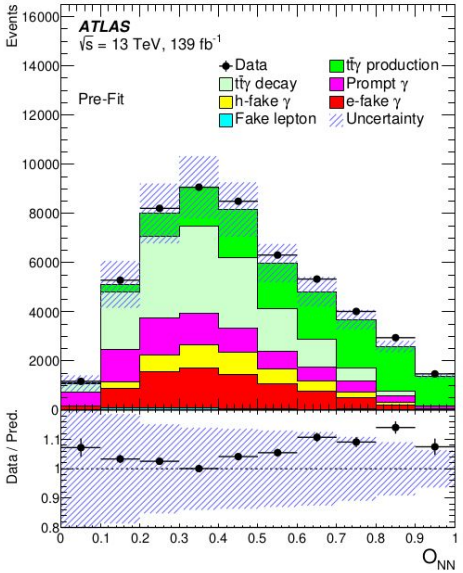
Fiducial:
- Exactly one lepton
- Exactly one prompt photon
- At least 4 jets, at least one of them b-jet

- Asymmetry measured via profile-likelihood unfolding, 2 bins at truth-level
- NN trained to identify $t\bar{t}\gamma$ signal - 2 regions defined: $O_{NN} > 0.6$ and $O_{NN} < 0.6$
- Only radiative photon production considered as signal
- Leading backgrounds: radiative $t\bar{t}$ decay, photon fakes

Charge asymmetry in $t\bar{t}\gamma$ at 13 TeV







$$A_c^{\text{NLO MC MG5 aMC@NLO+Pythia}} = -0.014 \pm 0.001$$

Leading uncertainties:

- Background modelling
- Jet reconstruction
- Fake-lepton estimate
- E_T^{miss}

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