$t\bar{t}X$ results from ATLAS and CMS

Large Hadron Collider Physics (LHCP) 2021 conference
Joint session on Higgs boson and top quark physics

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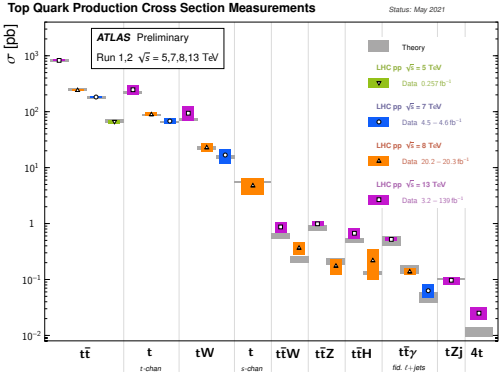
on behalf of the ATLAS and CMS collaborations

09/06/21

Introduction to $t\bar{t}X$ processes

- **Associated production of top-quark pairs**: $t\bar{t}X$ with $X \in \{W, Z, \gamma, H, t\bar{t}, q\bar{q}\}$
  - Allow to probe coupling of top quarks to EW bosons and rare SM processes $\rightarrow t\bar{t}Z/t\bar{t}\gamma$ and $t\bar{t}t\bar{t}$ processes covered in top quark physics session on Monday
  - $t\bar{t}H$ production covered in next talk by Djamel Eddine Boumediene

- This talk: **$t\bar{t}$W**, **$t\bar{t}b\bar{b}$** and **$t\bar{t}c\bar{c}$** production
  - Important backgrounds e.g. for $t\bar{t}H$ analyses
  - $t\bar{t}W$: rare $t\bar{t}X$ process with difficult modelling
  - $t\bar{t} + \mathrm{HF}$: high uncertainties in theoretical calc.
  - **Need precise knowledge of their properties**

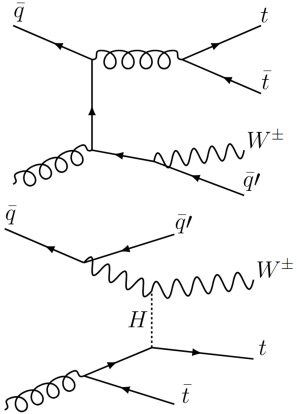


$t\bar{t}W$ production

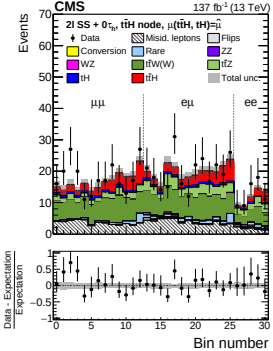
ATLAS paper ($36.1\,\mathrm{fb}^{-1}$): Phys. Rev. D 99 (2019) 072009
CMS paper ($35.9\,\mathrm{fb}^{-1}$): JHEP 08 (2018) 011

Introduction to $t\bar{t}W$ production

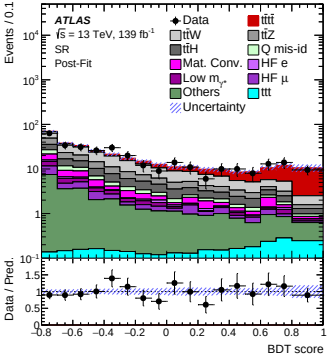
- $t\bar{t}W$ production at LO only from $q\bar{q}'$ initial states
  - **Large NLO corrections** due to additional gq initial states $\rightarrow$ difficult modelling
- Important background for analyses with **multilepton (ML) final states**
  - Examples: **$t\bar{t}H$ and $t\bar{t}t\bar{t}$ production**, searches for new physics, ...



Figures from arXiv:1907.04343



$2\ell SS$ channel in CMS $t\bar{t}H$ ML (Eur. Phys. J. C 81 (2021) 378)



ATLAS $t\bar{t}t\bar{t}$ ML analysis (Eur. Phys. J. C 80 (2020) 1085)

Selection of $t\bar{t}W$ production

- **Two main channels** for $t\bar{t}W$ selection ($\ell \in \{e, \mu\}$ incl. τ_{lep} decays)
  - 2ℓSS with $t\bar{t} \to (\ell^{\pm}\nu b)(q\bar{q}b)$ and $W^{\pm} \to \ell^{\pm}\nu$
  - 3ℓ with $t\bar{t} \to (\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$ and $W^{\pm} \to \ell^{\pm}\nu$
  - ATLAS analysis used both channels, CMS focussed on 2ℓSS channel

CMS 2ℓSS selection

Requirement	$2j$(p,m)	$3j\,1b$(p,m)	$3j > 1b$(p,m)	$> 3j\,1b$(p,m)	$> 3j > 1b$(p,m)
n_{jets}	2	3		> 3	
n_{bjets}	–	1	> 1	1	> 1
p_{T} (lead. ℓ)	$> 25\,\text{GeV}$ (40 GeV in ee case)				
p_{T} (sublead. ℓ)	$> 25\,\text{GeV}$				
$m_{\ell\ell}$	$> 12\,\text{GeV}$ and $\lvert m_{\ell\ell} - m_Z \rvert > 15\,\text{GeV}$				
$p_{\text{T}}^{\text{miss}}$	$> 30\,\text{GeV}$				

Requirement	2ℓ-SS(p,m)-$1b$	$2e$-SS(p,m)-$2b$	$e\mu$-SS(p,m)-$2b$	2μ-SS(p,m)-$2b$
$n_{b\text{-tags}}$	$=1$	≥ 2	≥ 2	≥ 2
$E_{\text{T}}^{\text{miss}}$	> 40 GeV	> 40 GeV	> 40 GeV	> 20 GeV
H_{T}	> 240 GeV			
p_{T} (leading lepton)	> 27 GeV			
p_{T} (subleading lepton)	> 27 GeV			
n_{jets}	≥ 4	≥ 4	≥ 4	≥ 2
Z veto	$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\text{GeV}$ in the $2e$ and 2μ regions			

ATLAS 2ℓSS selection

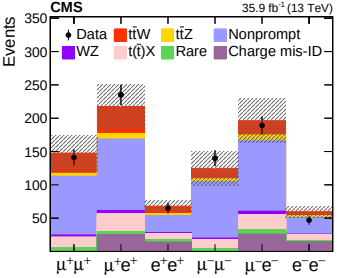
Variable	3ℓp-noZ-2b2j	3ℓm-noZ-2b2j	3ℓp-noZ-1b2j	3ℓm-noZ-1b2j
All leptons	$p_{\text{T}} > 27\,\text{GeV}$			
Z veto (OSSF pair)	$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\text{GeV}$			
n_{jets}	2 or 3			
H_{T}	–		> 240 GeV	
Sum of lepton charges	+1	−1	+1	−1
$n_{b\text{-tags}}$	≥ 2	≥ 2	1	1

ATLAS 3ℓ selection

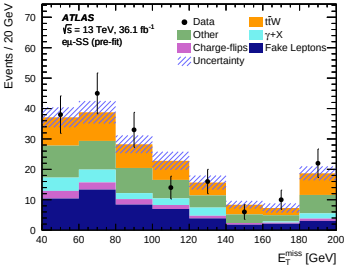
- Both experiments **split channels further** as a function of n_{jets}, n_{bjets} and lepton charge and **veto additional leptons** with looser ID and isolation requirements

Background processes and estimation

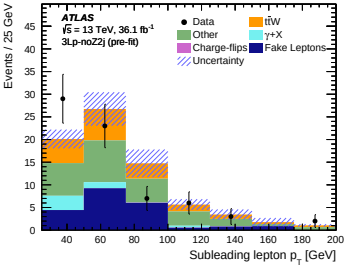
- Main **background processes**
  - $2\ell SS$: fake and non-prompt leptons, charge flip/mis-ID $e^{\pm}$, prompt processes (e.g. $t\bar{t}H$, WZ)
  - 3ℓ: fake and non-prompt leptons, prompt processes (e.g. $t\bar{t}H$ and $t\bar{t}Z$ in "Other" category)
- Estimation of **non-prompt and fake leptons**
  - Main sources: semi-leptonic b-hadron decays, photon conversions, misidentified hadrons, ...
  - Data-driven technique for both experiments with CRs for selection efficiency estimation



CMS $2\ell SS$ pre-fit yields split by lepton flavour/charge



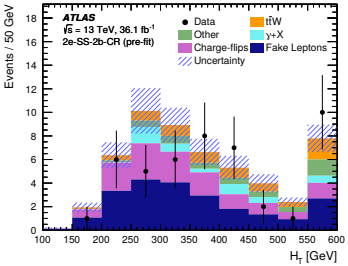
ATLAS $e^{\pm}\mu^{\pm}$ pre-fit agreement



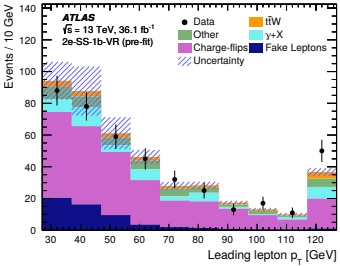
ATLAS 3ℓ pre-fit agreement

Background estimation and event selection

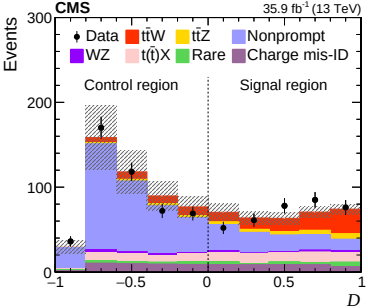
- Estimation of **charge flip/mis-ID electrons**
  - ATLAS applies data-driven technique using CR with $m_{\ell\ell}$ around m_Z
  - CMS estimates charge flip/mis-ID probabilities from MC and applies these to $2\ell\mathrm{OS}$ data
- **BDT-based event selection** in CMS analysis with BDT discriminant D
  - Input variables given e.g. as n_{jets}, n_{bjets}, $H_{\mathrm{T,jets}}$, $p_{\mathrm{T}}^{\mathrm{miss}}$, ... (11 in total)
  - Select only events with $D > 0$, further split into $0 < D < 0.6$ and $D > 0.6$ categories to increase sensitivity



ATLAS fake and non-prompt ℓ CR



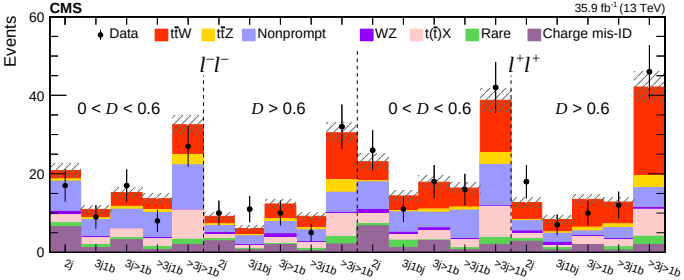
ATLAS charge flip/mis-ID $e^{\pm}$ CR



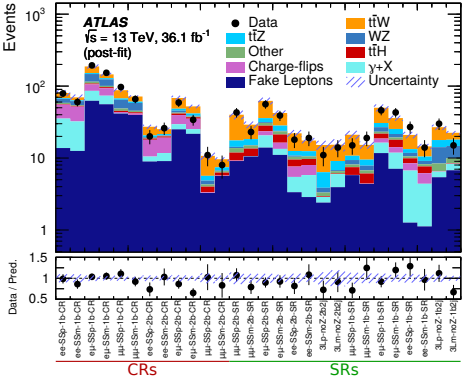
CMS event-selection BDT

Fit strategy and uncertainties

- Both experiments use **profile-likelihood fit** → figures show final data/MC agreement
- Dominant **systematic uncertainties**
  - ATLAS: $t\bar{t}W$ modelling, non-prompt/fake and charge flip/mis-ID estimation (incl. CR data stat.)
  - CMS: Trigger and b-tagging efficiencies, prompt and non-prompt/fake background estimation



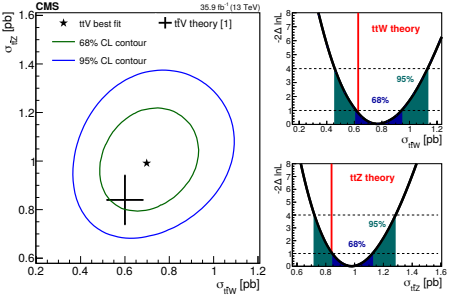
Post-fit agreement in CMS after the BDT selection



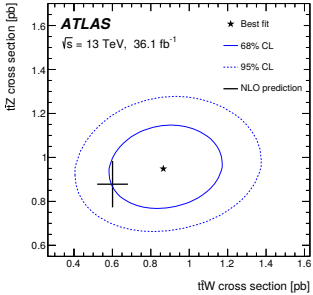
ATLAS post-fit agreement in CRs/SRs

Results on $t\bar{t}W$ production

- Results from **cross-section measurement** (in both cases $t\bar{t}V$ measurement)
  - ATLAS: $\sigma_{t\bar{t}W} = 0.87 \pm 0.13(\mathrm{stat}) \pm 0.14(\mathrm{syst})\,\mathrm{pb}$
  - CMS: $\sigma_{t\bar{t}W} = 0.77 \;^{+0.12}_{-0.11}(\mathrm{stat}) \;^{+0.13}_{-0.12}(\mathrm{syst})\,\mathrm{pb}$
  - Theory prediction: $\sigma_{t\bar{t}W} = 0.59^{+0.15}_{-0.10}(\mathrm{scale}) \pm 0.01(\mathrm{PDF})\,\mathrm{pb}$ (Eur. Phys. J. C 80 (2020) 428)



CMS $t\bar{t}V$ cross-section measurement



ATLAS $t\bar{t}V$ cross-section measurement

- CMS paper additionally includes **EFT interpretation** that includes $t\bar{t}W$ SRs
  - $t\bar{t}V$ analysis allows to constrain 8 Wilson coefficients, no operators only affect $t\bar{t}W$ alone

Results on $t\bar{t}W$ production

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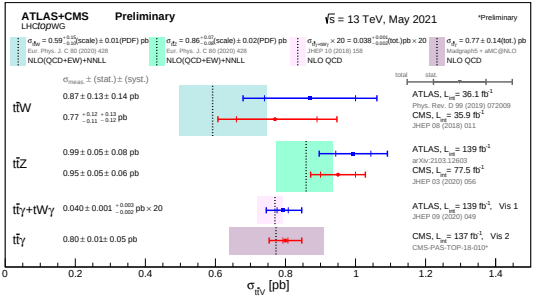

ATLAS + CMS $t\bar{t}V$ summary figure

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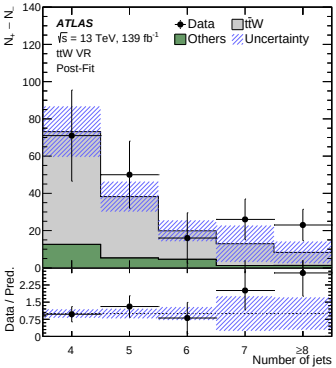
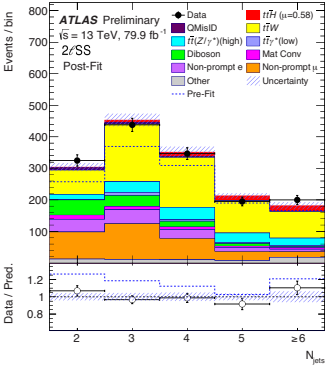
  - $t\bar{t}V$ analysis allows to constrain 8 Wilson coefficients, no operators only affect $t\bar{t}W$ alone

$t\bar{t}W$ production in recent $t\bar{t}H$ multilep. and $t\bar{t}t\bar{t}$ analyses

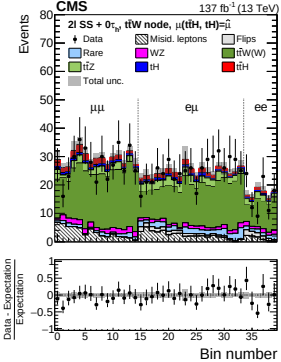
- Several analyses found **increased $t\bar{t}W$ yields w.r.t. theory prediction**
  - Typical normalisation factors in the range of $1.3 - 1.7 \times \sigma_{\text{theory}}$ (post-fit case shown below)
    $\rightarrow$ further mismodelling covered by additional systematics in some analyses
  - Clearly need to **improve theoretical and experimental understanding**



ATLAS $t\bar{t}t\bar{t}$ ML analysis
(Eur. Phys. J. C 80 (2020) 1085)



ATLAS $t\bar{t}H$ ML analysis
(ATLAS-CONF-2019-045)



CMS $t\bar{t}H$ ML analysis
(Eur. Phys. J. C 81 (2021) 378)

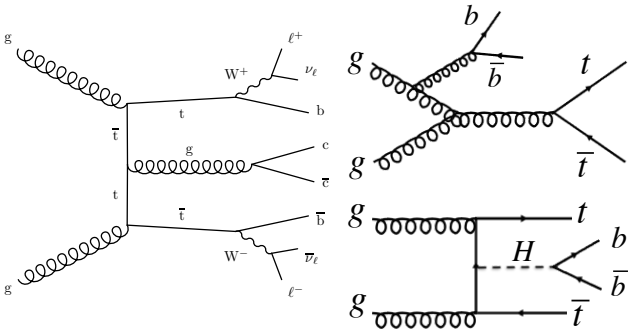
$t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$ production

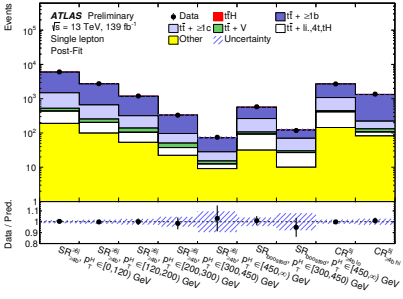
CMS $t\bar{t}c\bar{c}$ paper (dilepton $t\bar{t}$ decays, 41.5 fb^{-1}): submitted to Phys. Lett. B

ATLAS $t\bar{t}b\bar{b}$ paper ($e\mu$ and ℓ+jets $t\bar{t}$, 36.1 fb^{-1}): JHEP 04 (2019) 046
CMS $t\bar{t}b\bar{b}$ and $t\bar{t}j\bar{j}$ paper (dilepton and ℓ+jets $t\bar{t}$, 35.9 fb^{-1}): JHEP 07 (2020) 125
CMS $t\bar{t}b\bar{b}$ paper (all-hadronic $t\bar{t}$, 35.9 fb^{-1}): Phys. Lett. B 803 (2020) 135285

Introduction to $t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$ production

- $t\bar{t}b\bar{b}/t\bar{t}c\bar{c}$ production are **dominant backgrounds e.g. in $t\bar{t}H(b\bar{b})$ measurements**
  - Non-resonant background under peaking Higgs boson contribution
  - **Systematic uncertainties** in $t\bar{t}b\bar{b}$ prediction dominate inclusive $\mu_{t\bar{t}H}$ measurement
- **Theoretical modelling** of $t\bar{t}b\bar{b}/t\bar{t}c\bar{c}$ production is challenging
  - Uncertainties e.g. due to μ_F/μ_R scale choice

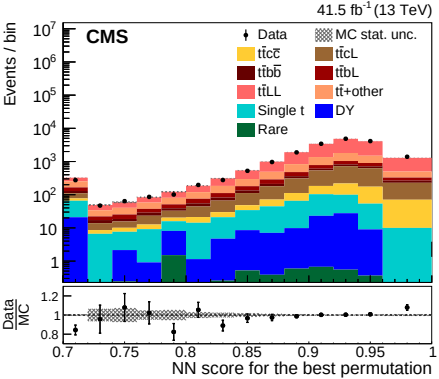




Single-ℓ CRs/SRs of ATLAS $t\bar{t}H(b\bar{b})$ analysis (ATLAS-CONF-2020-058)

$t\bar{t}c\bar{c}$ selection strategy and parton-matching

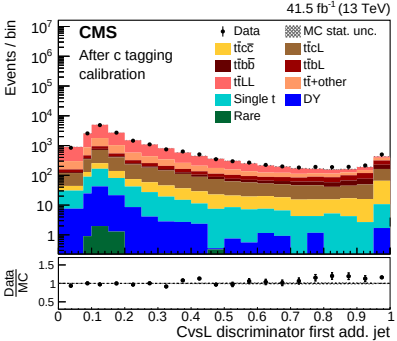
- **CMS $t\bar{t}c\bar{c}$ analysis** presented on the following slides
- **Event selection** with dileptonic $t\bar{t}$ decays
  - Two leptons (e or μ, incl. τ_{lep} decays) with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $|\eta| < 2.4$
  - $n_{\mathrm{jets}} \geq 4$ with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.4$ and $\Delta R(\ell, \mathrm{jet}) > 0.5$
  - $m_{\ell\ell} > 12\,\mathrm{GeV}$ for all events; $p_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$ and $|m_{\ell\ell} - m_Z| > 15\,\mathrm{GeV}$ in ee and $\mu\mu$ cases
- **Matching of jets and partons**
  - Two (b-)jets from top decays need to be identified
    $\rightarrow$ separate treatment of jets from add. radiation
  - NN trained for jet-parton assignment
    $\rightarrow$ use jet kinematics, b/c-tagging discriminators, ...
  - Loop over all permutations of jet-parton assignments
    $\rightarrow$ score indep. of assignment to top or anti-top quark
    $\rightarrow$ jets assigned to top quarks must both be b-tagged
  - Additional pair of **$c\bar{c}$ ($b\bar{b}$) jets identified in 50 (30)% of the cases**



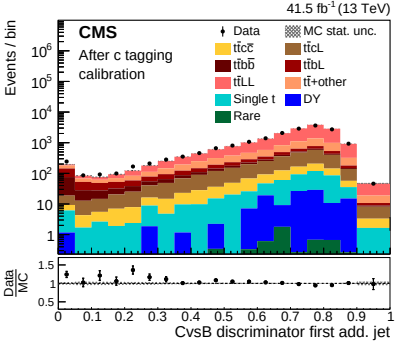
Parton-matching NN score

Identification of charm-jets

- **Tagging of single jets** performed with **multi-class DeepCSV algorithm**
  - Output classes: single b-hadron, two b-hadrons, one or more c-hadrons, light jets ($udsg$)
  - **Analysis uses two combinations**: $\mathrm{CvsL} = \frac{P(c)}{P(c)+P(udsg)}$ and $\mathrm{CvsB} = \frac{P(c)}{P(c)+P(b)+P(bb)}$
- **Dedicated calibration technique** for CvsL and CvsB scores
  - CRs: $t\bar{t}$ (for b-jets), $W + c$ (c-jets) and $\mathrm{DY} + \mathrm{jets}$ (light jets)



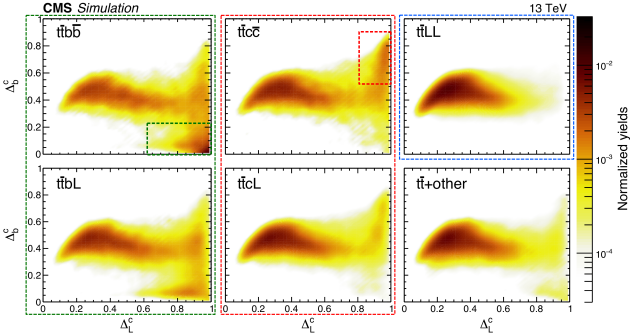
C vs. L discrimination for single jet



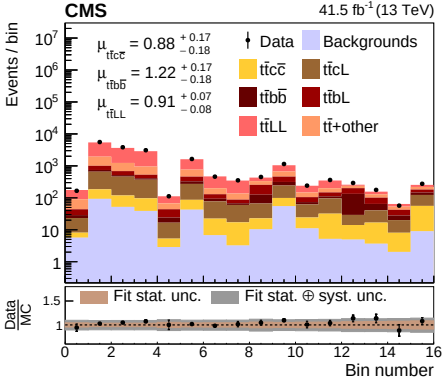
C vs. B discrimination for single jet

Fit strategy and MVA setup

- **Event-level separation** of $t\bar{t}b\bar{b}$, $t\bar{t}bL$, $t\bar{t}c\bar{c}$, $t\bar{t}cL$, $t\bar{t}LL$ and $t\bar{t}+\text{other}$ classes
  - Multi-class NN using CvsL/CvsB of leading two jets, $\Delta R(\text{jet},\text{jet})$ and permutation score
  - **Two discriminators**: $\Delta_b^c = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c})+P(t\bar{t}b\bar{b})}$ and $\Delta_L^c = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c})+P(t\bar{t}LL)}$
- Final fit done in **unrolled Δ_L^c vs. Δ_b^c distribution**
  - $\Delta_L^c \otimes \Delta_b^c$: $[0, 0.45, 0.6, 0.9, 1.0] \otimes [0, 0.3, 0.45, 0.5, 1.0]$



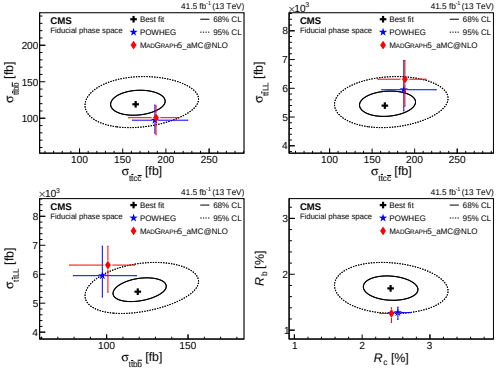
Δ_L^c vs. Δ_b^c 2D distributions



One-dimensional representation of binned Δ_L^c vs. Δ_b^c distribution

Results of cross-section and R_b/R_c measurements

- Measurement of $\mathbf{t\bar{t}b\bar{b}}$ (incl. $t\bar{t}bL$), $\mathbf{t\bar{t}c\bar{c}}$ (incl. $t\bar{t}cL$) and $\mathbf{t\bar{t}LL}$ production as well as $\mathbf{R_b} = t\bar{t}b\bar{b}/t\bar{t}jj$ and $\mathbf{R_c} = t\bar{t}c\bar{c}/t\bar{t}jj$ (separate fit) in **fiducial and full phase space**
  - Merged $t\bar{t}b\bar{b}/t\bar{t}bL$ and $t\bar{t}c\bar{c}/t\bar{t}cL$ categories $\rightarrow 2^{\mathrm{nd}}$ b/c-jet outside of accep. or merged with 1st jet
  - $t\bar{t}b\bar{b}$ yields slightly higher than predicted, $t\bar{t}c\bar{c}$ and $t\bar{t}LL$ yields slightly lower
  - Main uncertainties: c-tagging calib., JES unc., ME/PS matching, $\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$ scales in ME calc.



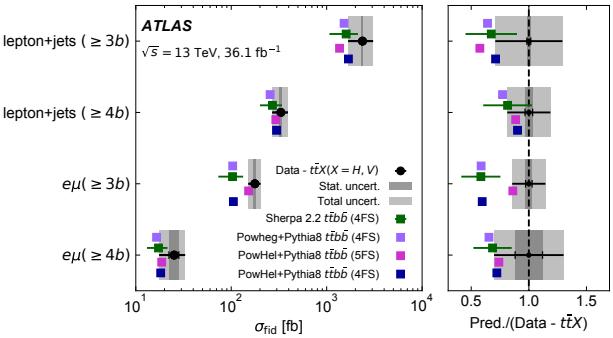
Results from simultaneous fit

	Result	POWHEG	MadGraph5_aMC@NLO
	Fiducial phase space		
$\sigma_{t\bar{t}c\bar{c}}$ [pb]	$0.165 \pm 0.023 \pm 0.025$	0.187 ± 0.038	0.189 ± 0.032
$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$0.119 \pm 0.010 \pm 0.015$	0.097 ± 0.021	0.101 ± 0.023
$\sigma_{t\bar{t}LL}$ [pb]	$5.40 \pm 0.11 \pm 0.45$	5.95 ± 1.02	6.32 ± 0.94
R_c [%]	$2.42 \pm 0.32 \pm 0.29$	2.53 ± 0.18	2.43 ± 0.17
R_b [%]	$1.75 \pm 0.14 \pm 0.18$	1.31 ± 0.12	1.30 ± 0.16
	Full phase space		
$\sigma_{t\bar{t}c\bar{c}}$ [pb]	$8.0 \pm 1.1 \pm 1.3$	9.1 ± 1.8	8.9 ± 1.5
$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$4.09 \pm 0.34 \pm 0.55$	3.34 ± 0.72	3.39 ± 0.66
$\sigma_{t\bar{t}LL}$ [pb]	$231 \pm 5 \pm 21$	255 ± 43	261 ± 37
R_c [%]	$2.69 \pm 0.36 \pm 0.32$	2.81 ± 0.20	2.72 ± 0.19
R_b [%]	$1.37 \pm 0.11 \pm 0.14$	1.03 ± 0.08	1.03 ± 0.09

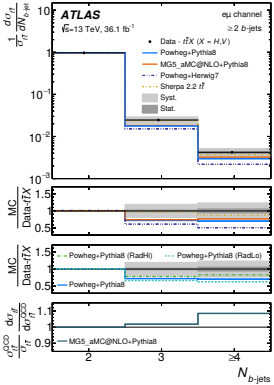
Fiducial and full phase space results

Measured $t\bar{t}b\bar{b}$ cross-sections and differential distributions

- ATLAS $e\mu/\ell$+jets analysis shows higher than predicted $t\bar{t}b\bar{b}$ yields within fid. volume
  - Analysis provides **inclusive and differential cross-section measurements**
  - Differential distribution of $\mathbf{n_{bjets}}$ **with clear trend**
    $\rightarrow$ other observables well described by most MC predictions in both channels



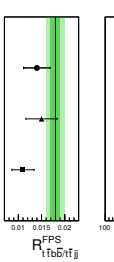
Fiducial measurement of $t\bar{t}b\bar{b}$ cross-sections



Unfolded n_{bjets} distribution for $e\mu$ case

Measured $t\bar{t}b\bar{b}$ cross-sections at CMS

- **Two separate analyses from CMS for $t\bar{t}b\bar{b}$** covering different $t\bar{t}$ decays
  - $t\bar{t}b\bar{b}$ yields in dilepton/ℓ+jets higher than predicted, while $t\bar{t}j\bar{j}$ yields show good agreement
  - All-hadronic $t\bar{t}b\bar{b}$ yields in parton-independent (PI) and -based (PB) fiducial volumes
    $\rightarrow$ increased $t\bar{t}b\bar{b}$ yield w.r.t. prediction again observed



Dilepton $t\bar{t}$ decays | ℓ+jets $t\bar{t}$ decays | All-hadronic $t\bar{t}$ decays

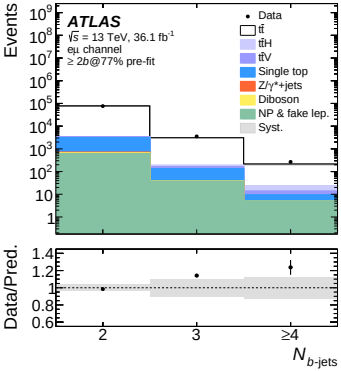
Summary

- Presented experimental status of $\mathbf{t\bar{t}W}$, $\mathbf{t\bar{t}b\bar{b}}$ and $\mathbf{t\bar{t}c\bar{c}}$ production
- $\mathbf{t\bar{t}W}$ production
  - Important background in analyses with **multilepton final states** (e.g. $t\bar{t}H$ and $t\bar{t}t\bar{t}$)
  - Both collaborations observe **higher yields than predicted** with $36\,\mathrm{fb}^{-1}$ of data
  - Recent $t\bar{t}H$ and $t\bar{t}t\bar{t}$ analyses also observe high normalisation factors
- $\mathbf{t\bar{t}b\bar{b}}$ and $\mathbf{t\bar{t}c\bar{c}}$ production
  - Important backgrounds in analyses like $\mathbf{t\bar{t}H(b\bar{b})}$
  - CMS provided **first dedicated measurement of $\mathbf{t\bar{t}c\bar{c}}$** production
    $\rightarrow$ $t\bar{t}b\bar{b}$ yields slightly higher than predicted, $t\bar{t}c\bar{c}$ and $t\bar{t}LL$ yields slightly lower
  - Generally **$\mathbf{t\bar{t}b\bar{b}}$ measurements found higher yields than predicted**
    $\rightarrow$ normalisation factors of $1.2 - 1.7 \times \sigma_{\mathrm{Powheg+Pythia8}}$ (typically 1-2 standard deviations)
- **Stay tuned for full Run 2 results on these processes!**
  - Clearly need to improve theoretical and experimental understanding

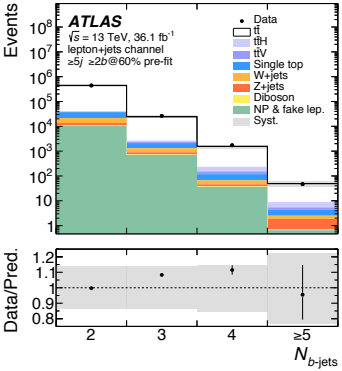
Backup

Event selection in ATLAS $t\bar{t}b\bar{b}$ analysis

- Here: ATLAS $e\mu/\ell$+jets analysis at $36.1\,\mathrm{fb}^{-1}$
- **Baseline selection** requires $n_{\mathrm{jets}} \geq 2\,(5)$ and $n_{\mathrm{bjets}} \geq 2\,(2)$ in $e\mu$ (ℓ+jets) channels



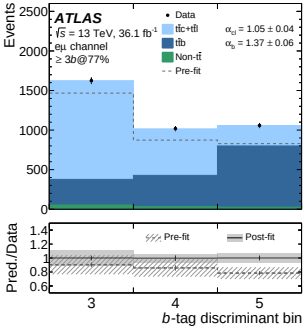
Baseline data/MC agreement in $e\mu$ channel



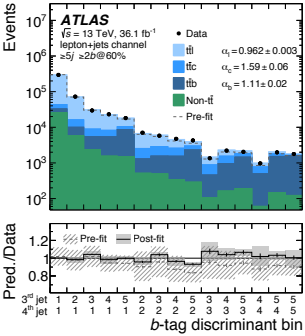
Baseline data/MC agreement in ℓ+jets channel

Correction factors for $t\bar{t}c$ and $t\bar{t}l$ backgrounds

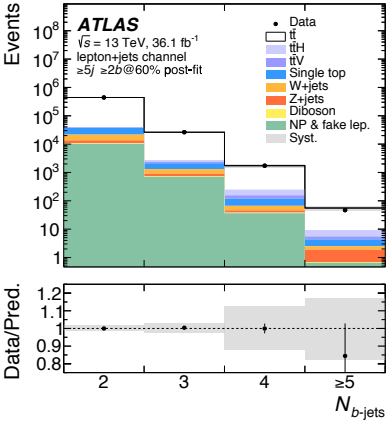
- Normalisation of **$t\bar{t}c$ and $t\bar{t}l$ backgrounds** estimated in template fits
  - Binned vs. b-tagging discriminant of 3rd (3rd and 4th) leading jet in $e\mu$ (ℓ+jets) channels
- Data/MC agreement improved for baseline selection



$e\mu$ correction factors



ℓ+jets correction factors



ℓ+jets data/MC agreement after correction
(impact on $e\mu$ channel very similar)