ATLAS results on $t\bar{t}$ + heavy flavor measurements

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U.S. DEPARTMENT of ENERGY

Introduction

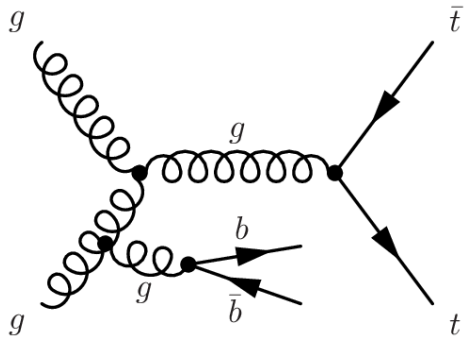
- Thirty years after its discovery, the top quark remains a cornerstone of modern particle physics research
  - Heaviest quark with Yukawa coupling to the Higgs boson of the order of 1
  - Decays into a W and b-quark before hadronization: the only quark that behaves as a free one
- $t\bar{t}$ production in association with heavy flavor (b/c) jets ($t\bar{t}$+HF) is particularly important as it is the dominant background to $t\bar{t}$H and 4-top processes
  - $t\bar{t}$H: direct measurement of top Yukawa coupling y_t
  - 4-top (first observed in 2023): probing CP-properties of y_t
- This talk is based on two recent ATLAS publications based on Run 2 data
  - Measurement of $t\bar{t}$ production in association with additional $\boldsymbol{b}$-jets in the $\boldsymbol{e\mu}$ final state ($t\bar{t}$+b)
  - Measurement of top-quark pair production in association with charm quarks ($t\bar{t}$+c)

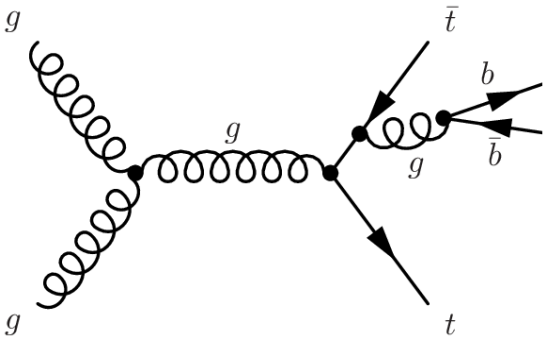
$t\bar{t}$+b

- Measurement of $t\bar{t}$ production in association with additional $\boldsymbol{b}$-jets in the $\boldsymbol{e\mu}$ final state
  - JHEP 01 (2025) 068

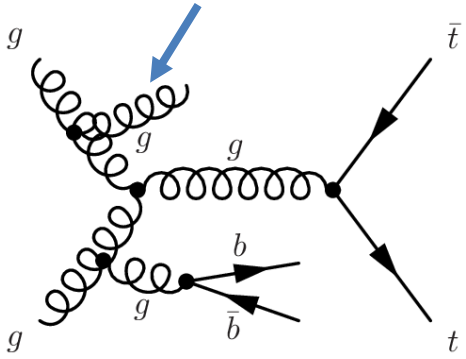
$t\bar{t}$+b production

gluon splitting

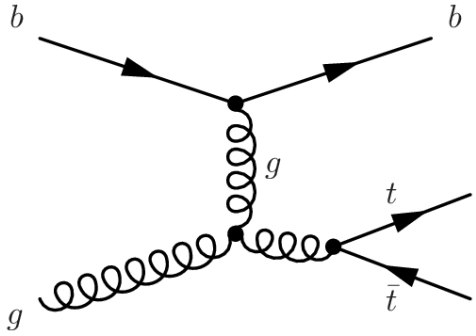




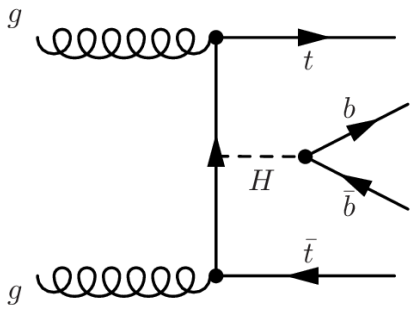
additional jets

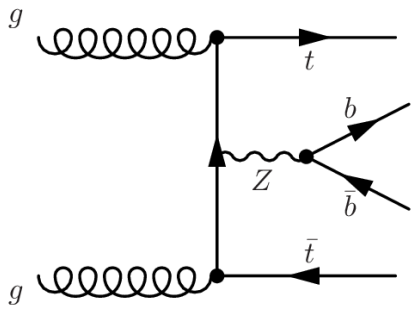


initiated by a b-quark



resonant production



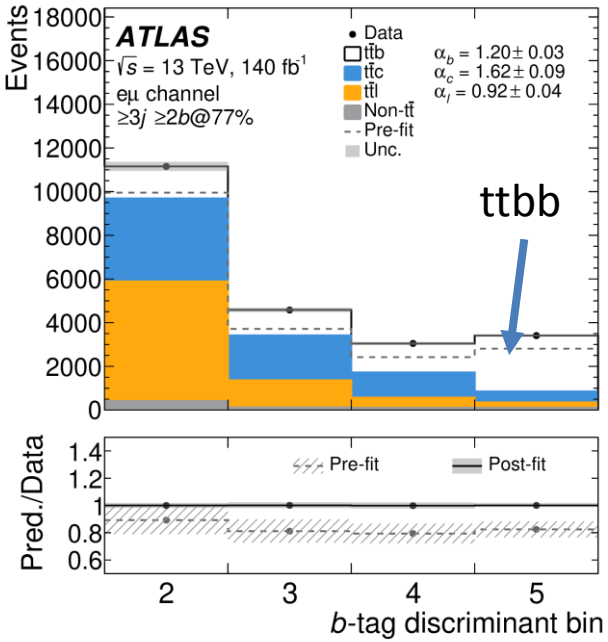


Event selection

- Data sample: 140/fb of data collected by ATLAS in 2015-18
  - single e/μ triggers
  - $t\bar{t}$→eμ channel: events are required to have exactly one isolated electron and muon of opposite charge
  - $t\bar{t}$+b signal: at least three b-tagged jets (DL1d tagging algorithm at ε_b=77% working point)
- Measured cross sections refer to fiducial phase spaces defined at the particle level
  - events are required to have exactly one particle-level electron and muon of opposite charge
  - jets are built using anti-kT R=0.4 algorithm from all stable particles excluding prompt e/μ and ν from W decays
  - b-jets are defined by presence of a B-hadron via ghost association
  - e/μ must be separated from jets by ΔR>0.4
- Four phase spaces: ≥3b, ≥4b, ≥3b ≥1l/c, ≥4b ≥1l/c

How to extract the $t\bar{t}$+b fraction?

- Can't just count the number of events with ≥3 or ≥4 tagged jets
  - only ~50% of events with ≥3 b-tagged jets contain ≥3 true b-jets
  - flavor composition of additional jets is not correctly predicted by MC
- Solution: data driven approach
  - derive the $t\bar{t}$b, $t\bar{t}$c, and $t\bar{t}$l templates for the third-highest b-tagging discriminant in the event
  - "Global fit": fit the b-tagging discriminant distribution in data to a weighted sum of tt+HF MC templates



1d fit in inclusive 3j2b region

- Note: charm scale factors are consistently >1
  - e.g. global fit in the ≥3j≥2b inclusive region yields α_s^c=1.62±0.09

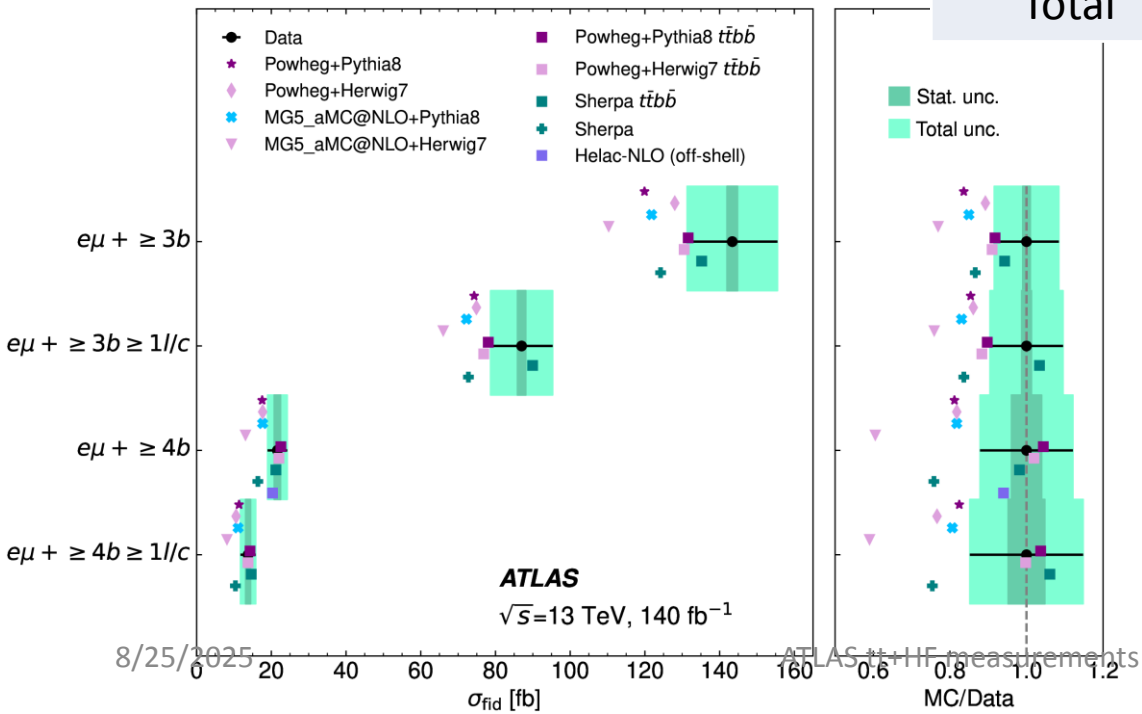
$t\bar{t}$+b modeling

- $t\bar{t}$ simulations: NLO in QCD ME in 5FS (massless b-quarks) interfaced to PS
  - Powheg + Pythia 8 / Herwig 7
  - MadGraph5_aMC@NLO + Pythia 8 / Herwig 7
  - Sherpa: NLO up to one additional parton + LO up to four additional partons merged with Sherpa PS
- $t\bar{t}$+$b\bar{b}$ simulations: NLO in QCD ME in 4FS (additional massive b-quarks included at the ME level)
  - Powheg + Pythia 8 / Herwig 7
  - Sherpa: NLO ME merged with Sherpa PS
  - Helac-NLO: $e\nu_e\mu\nu_\mu b\bar{b}b\bar{b}$ including non-resonant top contributions

Fiducial cross section measurements

- Measured cross sections:
  - ≥3b: 143±1(stat)±12(syst) fb
  - ≥3b ≥1l: 87±1(stat)±8(syst) fb
  - ≥4b: 22±1(stat)±3(syst) fb
  - ≥4b ≥1l: 14±1(stat)±2(syst) fb

Uncert. (%)	≥3b	≥4b	≥3b ≥1l	≥4b ≥1l
Statistics	1.0	1.2	3.9	4.8
Detector	6.7	7.6	9.7	11.2
$t\bar{t}$ modeling	5.2	5.7	7.2	9.7
Total	8.5	9.6	12.7	15.5

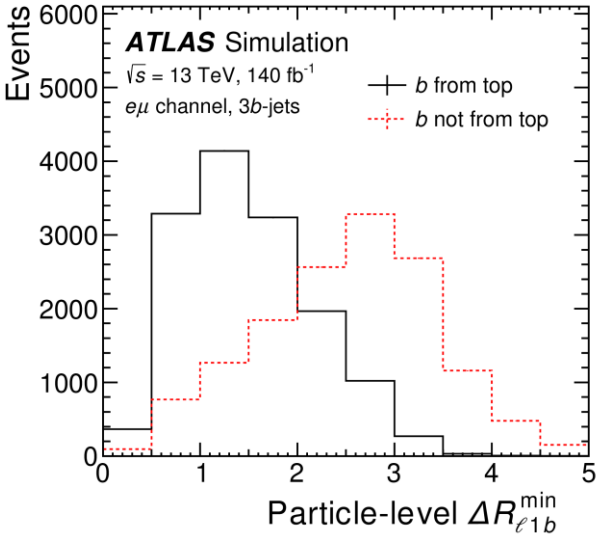


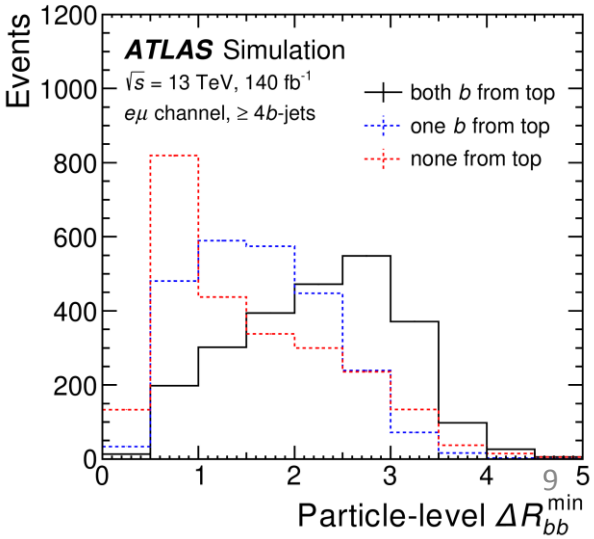
- Measurement precision is best to date in the channel, better than theory NLO predictions (20-50%)
- $t\bar{t}$ models tend to yield lower $t\bar{t}$+b rates compared to $t\bar{t}b\bar{b}$ models

Differential distributions

- Measured differential distributions are unfolded to particle level using iterative Bayesian unfolding
  - subtract MC derived backgrounds (single top, VV, ttV, ttH)
  - correct contributions from various tt+HF based on the global fit
  - invert the migration matrix
- Distributions referring to additional b-jets: which jets are additional?
  - use empirical algorithm based on jet kinematics

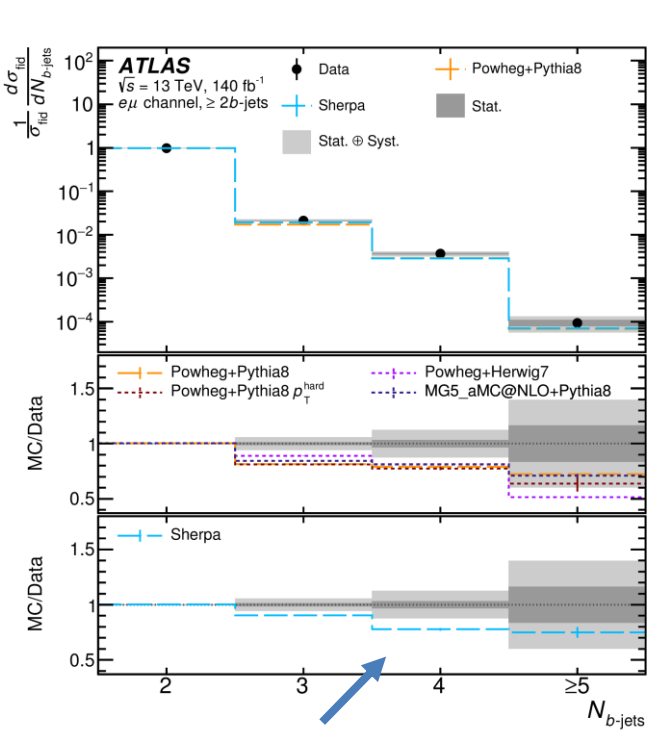
$$-\ln w = (\Delta R_{l1b1} - \Delta R_{l1b}^{\min})^2 + (\Delta R_{l2b2} - \Delta R_{l2b}^{\min})^2 + \begin{cases} (\max(\Delta R_{b1b3}, \Delta R_{b2b3}) - \Delta R_{bb}^{\max})^2 & \text{if } N_{b\text{-jets}} = 3, \\ (\Delta R_{b3b4} - \Delta R_{bb}^{\min})^2 & \text{if } N_{b\text{-jets}} \geq 4 \end{cases}$$



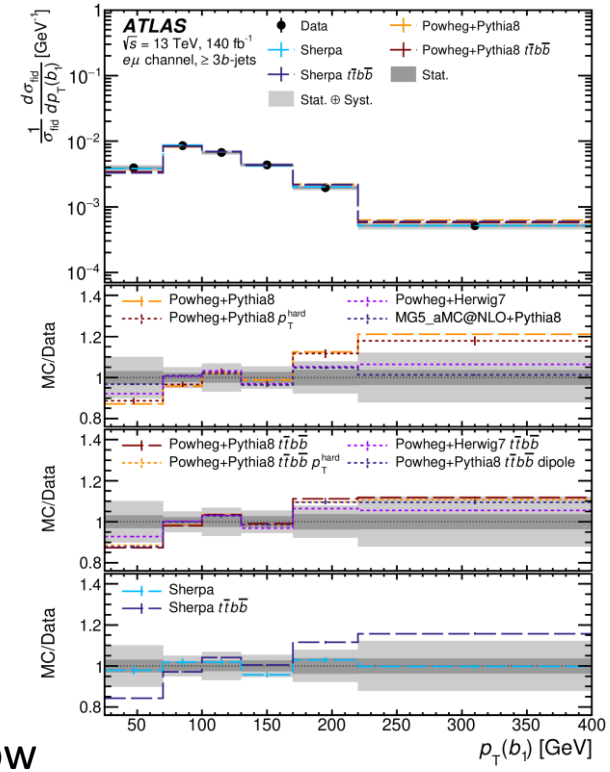


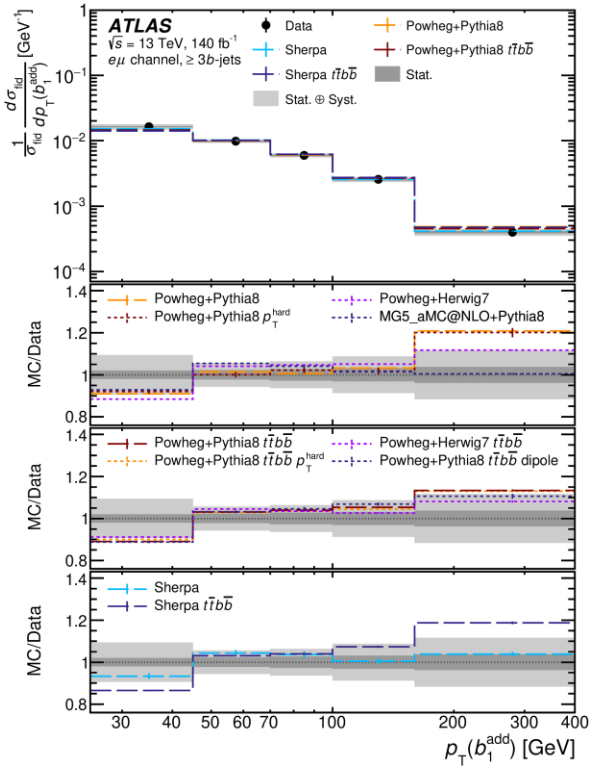
Differential distributions (2)

- Variable degrees of agreement for different MC, e.g Sherpa has better b-jet p_T description than Sherpa $t\bar{t}b\bar{b}$
- All simulations tend to underestimate the b-jet multiplicity



predicted b-jet multiplicity too low



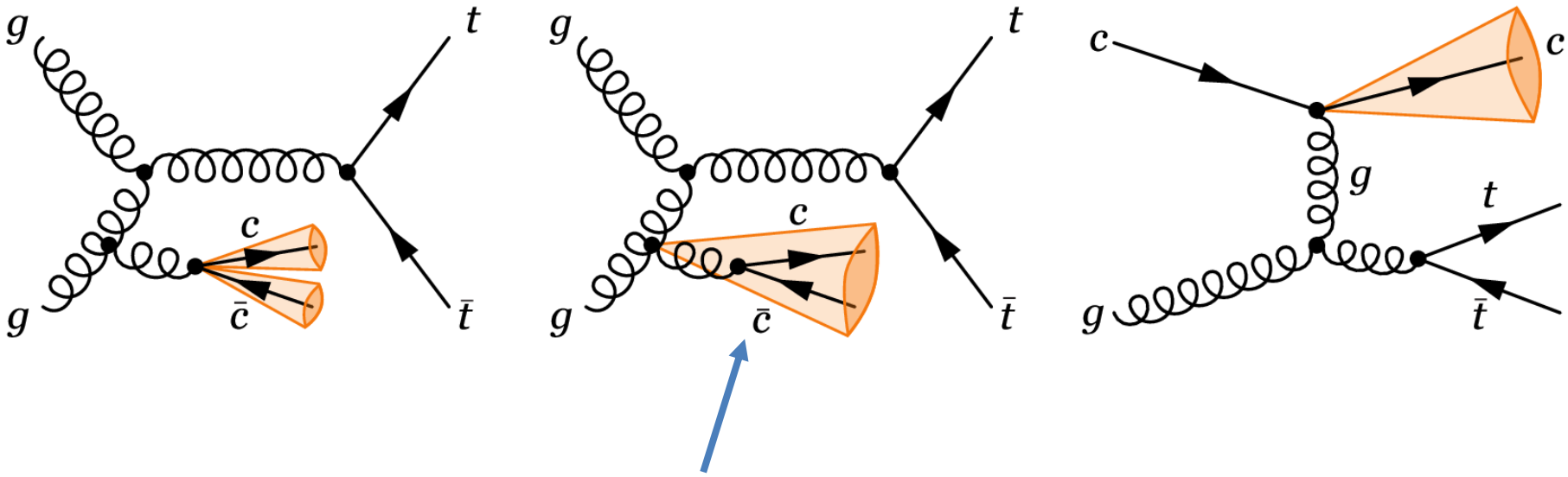


$t\bar{t}$+c

- Measurement of top-quark pair production in association with charm quarks
  - Phys. Lett. B 860 (2025) 139177

$t\bar{t}$+c production

- Perform separate measurement of $t\bar{t}$+1c and $t\bar{t}$+≥2c

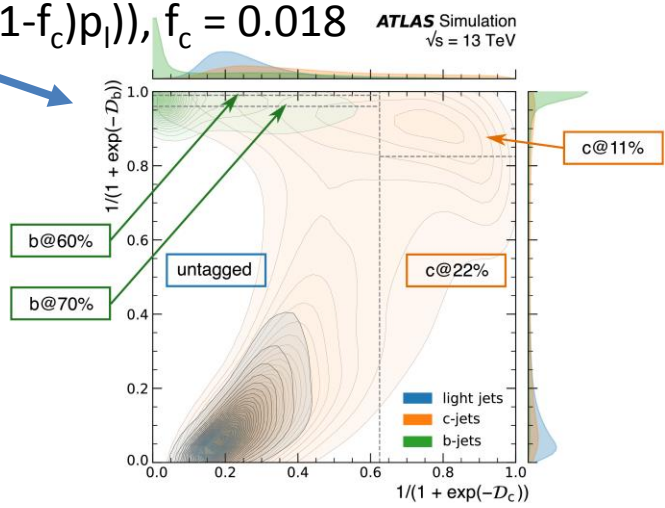


one jet, two c-quarks

Event selection

- Data sample: 140/fb of data collected by ATLAS in 2015-18
  - single e/μ triggers
  - events are required to have exactly one isolated electron and muon of opposite charge with p_T>10 GeV
- Several signal regions: single lepton or dilepton channels, Njets, b/c tagger output

$D_b=\log(p_b/(f_c p_c+(1-f_c)p_l))$, f_c = 0.018



$D_c=\log(p_c/(f_b p_b+(1-p_b)p_l))$, f_b=0.4

2-D b/c-tagging: DL1r

suffer from W→cs

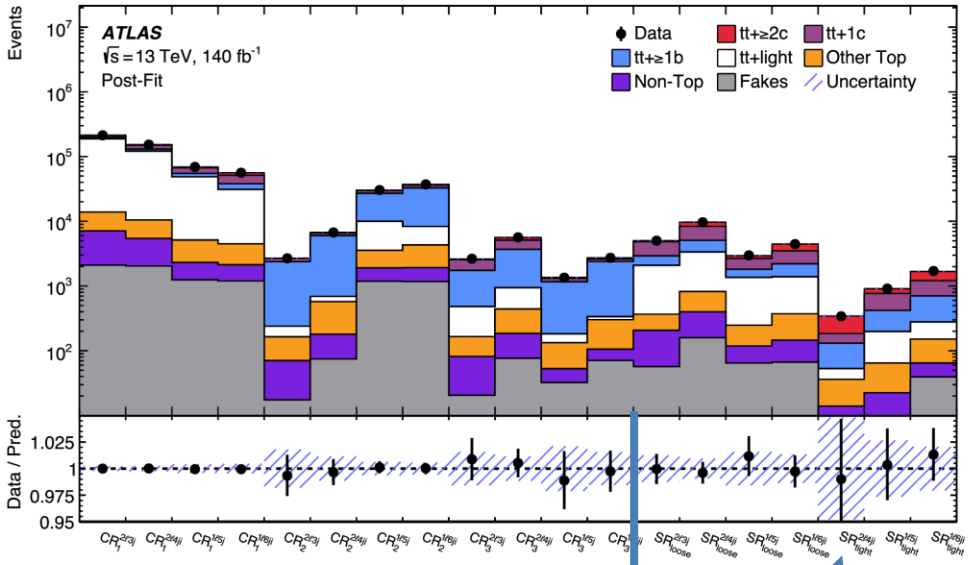
	$CR_1^{1\ell}$	$CR_2^{1\ell}$	$CR_3^{1\ell}$	$SR_{loose}^{1\ell}$	$SR_{tight}^{1\ell}$	$CR_1^{2\ell}$	$CR_2^{2\ell}$	$CR_3^{2\ell}$	$SR_{loose}^{2\ell}$	$SR_{tight}^{2\ell}$
N_{jets}	= 5 or ≥ 6					= 3 or ≥ 4				≥ 4
b@70%	2	–	–	2	2	2	–	≥ 3	2	2
b@60%	–	≥ 3	3	–	–	–	≥ 3	≤ 2	–	–
c@22%	1	0	1	≥ 2	–	0	–	–	1	≥ 2
c@11%	1	–	1	1	≥ 2	–	–	–	–	–

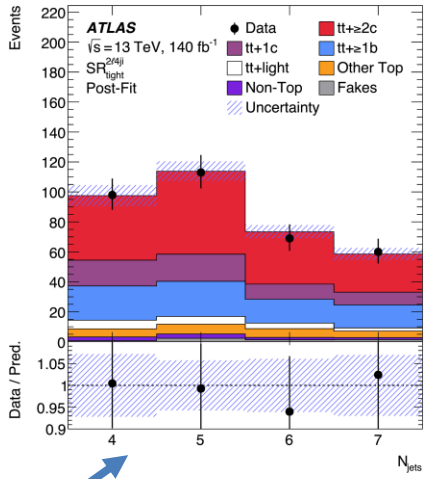
6×2=12 CR

3×2+1=7 SR

Extraction of results

- Approach: simultaneous fit to the number of events in each region
  - SR: add invariant mass of tagged jets to mitigate the W→cs contribution





control regions: low charm

SR 2l4j tight: cleanest tt+cc sample, lowest statistics

MC derived backgrounds: single top, ttV, dibosons, V+jets
Instrumental backgrounds (relevant for 1l regions): fake leptons, data-driven estimate

Measured cross sections

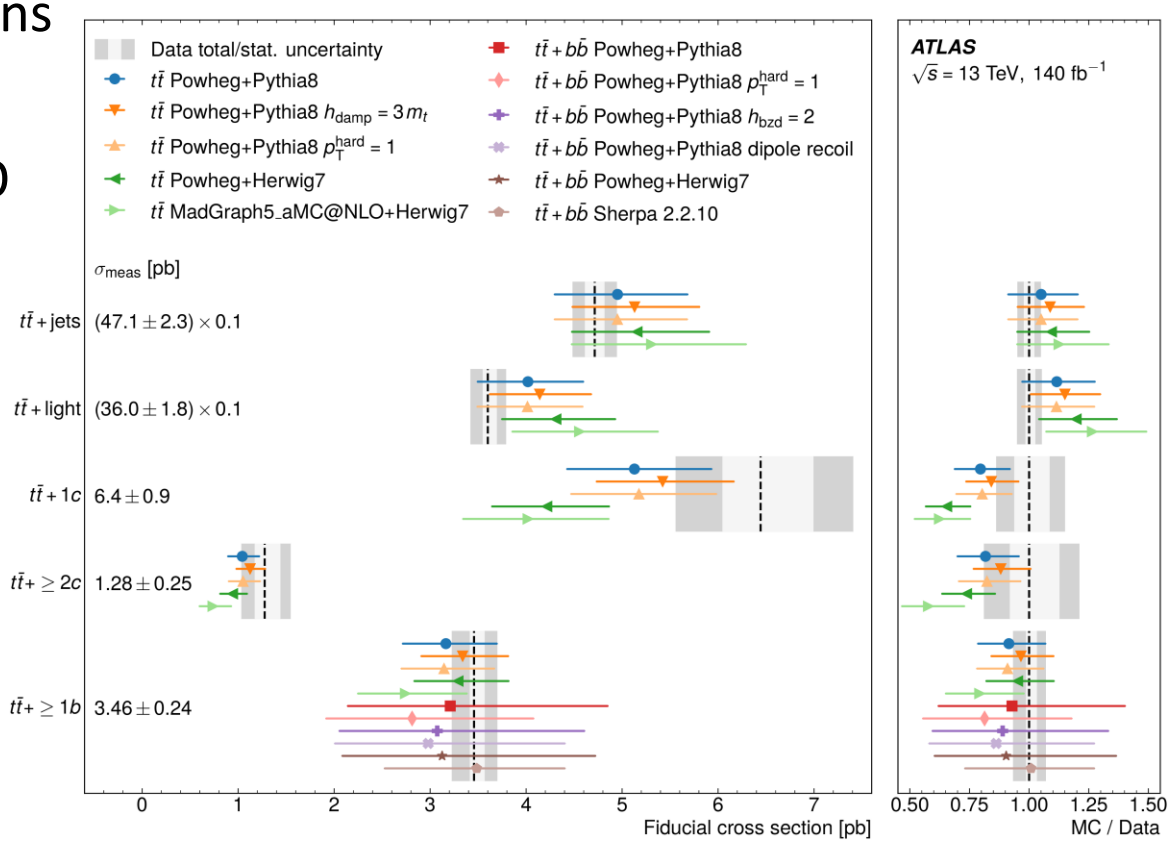
- Cross sections are reported in fiducial volume
  - dilepton: exactly two opposite charged leptons (e/μ), ≥3 particle level jets of which ≥2 are ghost-associated with B-hadrons
  - single lepton: exactly one lepton, ≥5 particle level jets of which ≥2 are ghost-associated with B-hadrons
  - this definition accepts ~17% of simulated $t\bar{t}$+≥1c events

Uncert. (%)	tt+≥2c	tt+1c
tt+c modeling	9	8
background	8	6
instrumental	11	7
MC stat	3.1	2.5
data stat	11	7
Total	20	14

- Measured fiducial cross sections:
  - $t\bar{t}$+1c: 6.4+1.0−0.9 pb (8.8±1.3% of total $t\bar{t}$+jets production)
  - $t\bar{t}$+≥2c: 1.28+0.27−0.24 pb (1.23±0.25% of total $t\bar{t}$+jets production)

Comparison to MC predictions

- Powheg+Pythia8 setups agree with the measured values within 0.5 to 1.1 standard deviations
- Powheg+Herwig7 and MadGraph5_aMC@NLO +Herwig7 predict cross-sections up to 40% lower than the measurements, with agreement observed at the level of up to 2.0 standard deviations.



Conclusions

- Presented results provide crucial insights into $t\bar{t}$+HF production
  - first detailed study of kinematic properties of the events
  - first dedicated measurement of $t\bar{t}$+c by ATLAS
- The results reveal challenges in current theoretical models
  - improving these model will be essential for better background estimations for rear physics processes like $t\bar{t}$H and 4-top production
- These advancements improve our understanding of fundamental interactions within the Standard Model as well as pave the way for discoveries that could push the boundaries of known physics.

Physics Briefing