$t\bar{t}t\bar{t}$ production and flavor tagging with ATLAS

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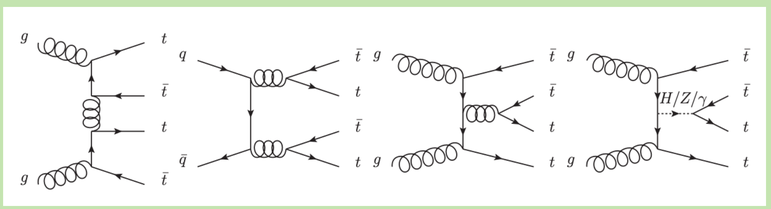
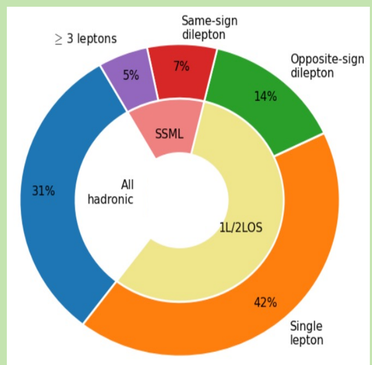
① Introduction

- Heaviest final state and one of the rarest processes predicted by the SM at the LHC. The multilepton final state is especially sensitive to new physics.
- Observed by ATLAS in 2023 using the full Run 2 dataset of $139\ \text{fb}^{-1}$ at $\sqrt{s} = 13\ \text{TeV}$, with a measured $\sigma_{t\bar{t}t\bar{t}} = 22.5\ \text{fb}$ consistent with SM prediction within 1.8σ [1]. Similar results were also observed with CMS at 5.6σ observed significance level[2].
- The analysis will be continued using Run 3 data at $\sqrt{s} = 13.6\ \text{TeV}$ and increased luminosity. The Run 3 analysis will also use improved b-taggers DL1dv01 and GN2, currently being calibrated using multi-jet events.



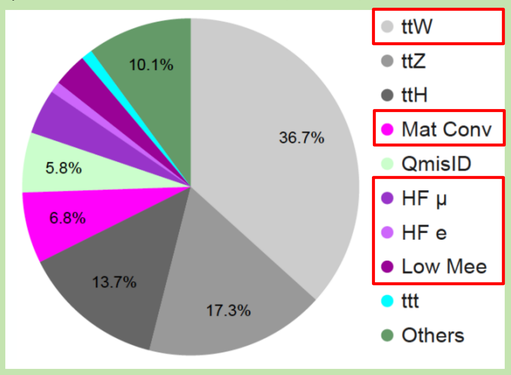
② $t\bar{t}t\bar{t}$ process

- Sensitive to new physics due to t heavy mass.
- Extremely small cross section, $\mathrm{O}(10^5)$ lower than $\sigma_{t\bar{t}}$.
- Decay product: $t\bar{t}t\bar{t} \rightarrow 4W + 4b$
  - $W \rightarrow l\bar{\nu}_l$ (leptonic decay) or $W \rightarrow q\bar{q}$ (hadronic)
  - 0/1/2/3+ $l/\bar{\nu}_l$ pairs + 8/6/4/2- jets + 4 b-jets
- Same-sign/multilepton (SSML) signal region smallest but most sensitive



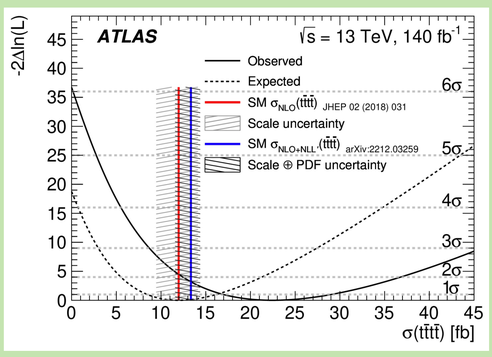
③ Analysis regions

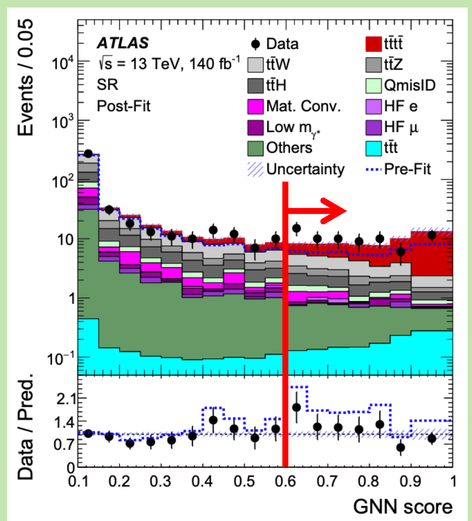
- **Signal region (SR):** 1 region
  - 6+ jets, at least 2 b-jets passing 77% WP
- **Control regions (CRs):** 8 regions
  - Physics/irreducible BGs: $t\bar{t}W$+jets
  - Instrumental/reducible BGs: non-prompt leptons
- Signal extraction: Multivariate discriminant based on graph neural network (GNN)

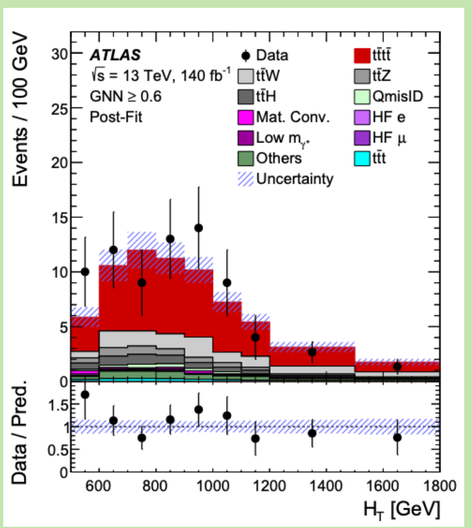


④ Cross section measurements

- $\sigma_{t\bar{t}t\bar{t}}$ was determined using a binned likelihood fit to the GNN score.
- Measured $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.5}\ \text{fb}$, consistent within 1.8σ with SM expectation of $\sigma_{t\bar{t}t\bar{t}} = 12.0\ \text{fb}$ at NLO in QCD with EW corrections[3].







	Pre-fit		Post-fit	
	SR	GNN≥0.6	SR	GNN≥0.6
Total bkg	390 ± 50	26 ± 5	412 ± 21	32 ± 4
$t\bar{t}t\bar{t}$	38 ± 4	25.2 ± 3.2	69 ± 15	45 ± 10
Total	430 ± 50	51 ± 7	480 ± 19	77 ± 8
Data	482	83	482	83

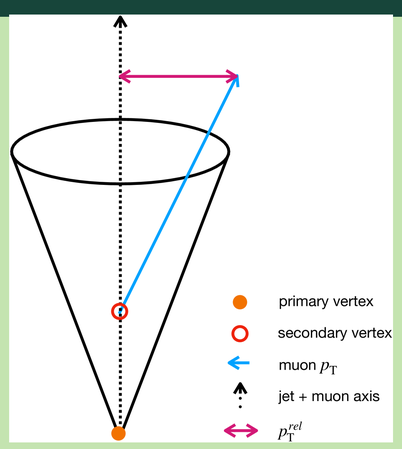
⑤ b-tagger calibration

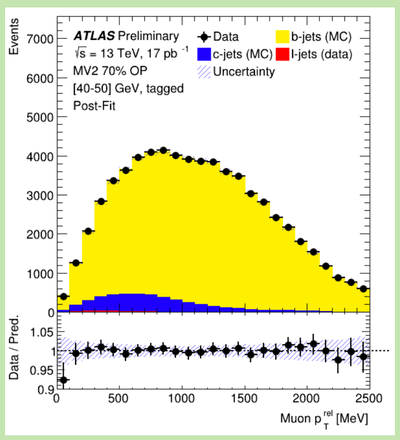
- b-tagging: very important for $t\bar{t}t\bar{t}$ event selection
- Multi-jet calibration[4]
  - Discriminant uses muons from b-hadron decays
  - Takes advantage of large $b\bar{b}$ cross section
  - Orthogonal sample to $t\bar{t}$-based LLH calibration

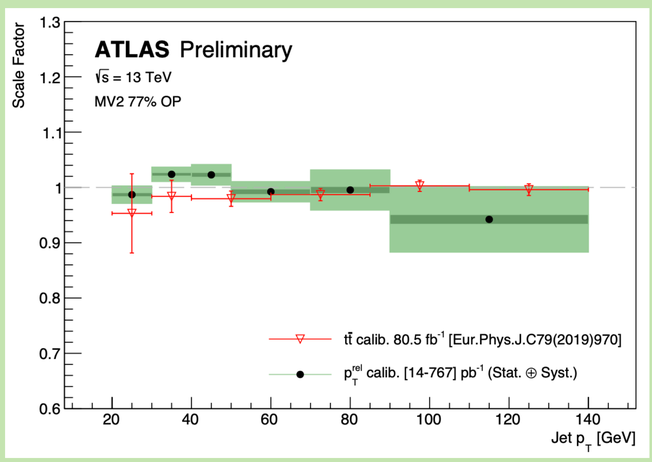
  → orthogonal set of scale factors & different sources of uncertainties/assumptions
- p_T^{rel} method[4]
  - Discriminant: muon p_T relative to the jet's axis

$$p_T^{rel} = \left\| \vec{p}_\mu \times \frac{\vec{p}_{jet} + \vec{p}_\mu}{\left\| \vec{p}_{jet} + \vec{p}_\mu \right\|} \right\|$$

- **Run 2 results**: p_T^{rel} method outperformed $t\bar{t}$-based calibration in the low jet p_T region (20 – 50 GeV) when performed on MV2 tagger.
- DL1dv01 is currently being calibrated with this method using MC simulations and data from Run 2. GN2 will also be calibrated similarly with the addition of Run 3 MC/data samples.







⑥ Run 3 prospects

- 18% increase in the $t\bar{t}t\bar{t}$ cross section (LO in QCD) from increased COM energy.
- Other improvements:
  - b-taggers (DL1dv01 & GN2)
  - Exploring different discriminator structures and algorithms
  - Continuous efforts to improve BG & signal modelling
    - Refining $t\bar{t}W$+jets BG data-driven estimation
    - $t\bar{t}t\bar{t}$ NLO studies and separation from signal
    - $t\bar{t}t\bar{t}$ generator choice
    - c- and light-flavor jet tagging

⑦ Summary

- Four top quark production process was observed at the LHC with ATLAS, with a measured cross section of $22.5\ \text{fb}$, consistent within 1.8σ with SM predictions.
- Precision measurements will be carried out with new Run 3 data.
- Run 3 calibration for new b-taggers underway to assist with the efforts.

References

1. ATLAS Collaboration, *Observation of four-top-quark production in the multilepton final state with the ATLAS detector*, Eur. Phys. J. C 83 (2023) 496, arXiv: 2303.15061 [hep-ex]
2. CMS Collaboration, *Observation of four top quark production in proton-proton collisions at* $\sqrt{s} = 13\ TeV$, (2023), CMS-PAS-TOP-22-013, URL: https://cds.cern.ch/record/2853304
3. R. Frederix, D. Pagani and M. Zaro, *Large NLO corrections in* $t\bar{t}W^{\pm}$ *and* $t\bar{t}t\bar{t}$ *hadroproduction from supposedly subleading EW contributions*, JHEP 02 (2018) 031, arXiv: 1711.02116 [hep-ph]
4. ATLAS Collaboration, *Measurement of the b-jet identification efficiency with the* p_T^{rel} *method in multi-jet events using pp collisions at* $\sqrt{s} = 13\ TeV$ *with the ATLAS Detector*, (2022), ATL-PHYS-PUB-2022-025, URL: https://cds.cern.ch/record/2809692

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