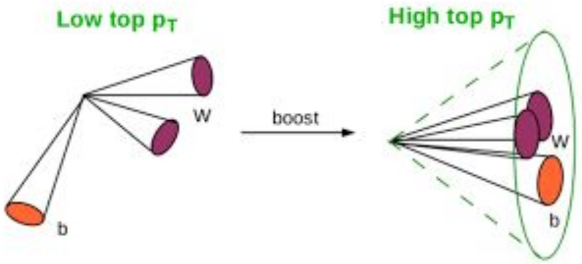
The 32nd Rencontres de Blois, October 17-22, 2021
Château of Blois, Loire Valley, France
Particle Physics and Cosmology

Testing the Standard Model in boosted top quark production with the ATLAS experiment at the LHC

Asma Hadef

Johannes Gutenberg-Universität Mainz

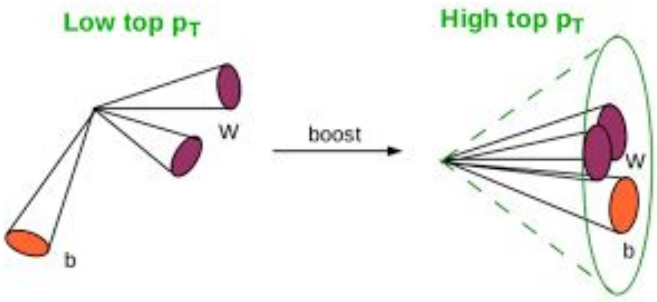
On behalf of the ATLAS collaboration



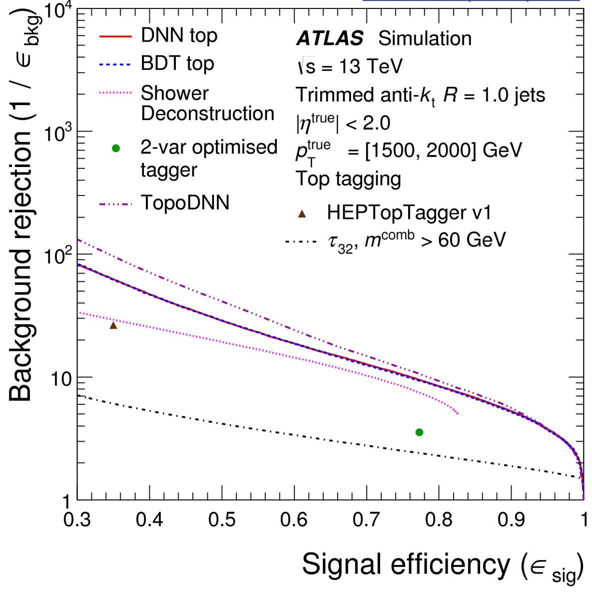
20.10.2021

Introduction

- **Top-quark physics** in the **boosted phase space** at the LHC is very well suited to deciphering possible UV theories (BSM @ high energies).
- Measurements are compared with SM predictions and they are used to set limits on the **Wilson coefficients** of the **effective field theory (EFT)**.
- Reconstructing and identifying boosted top @detector is needed.
- Hadronically decaying **boosted top** quarks:
  - $p_T > 2\ m_{top}$.
  - Decay products start to overlap $\rightarrow$ collimated in one **large-radius jet**.
  - Identification algorithms ("**taggers**") @ATLAS with multivariate techniques based on jet shape observables:
    - Jet moments || Topocluster-based Tagger (TopoDNN) || shower deconstruction || HEPTopTagger.



EPJC 79 (2019) 375



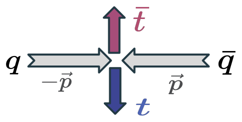
Boosted top @ATLAS

- $t\bar{t}j$ **energy asymmetry, 139 fb^{-1}:** New
  - ➢ Lepton+jets selection: arXiv:2110.05453 (2021)
- $t\bar{t}$ **rapidity asymmetry, 139 fb^{-1}:**
  - ➢ lepton+jets selection: ATLAS-CONF-2019-026
- $t\bar{t}$ **differential cross sections, 36 and 139 fb^{-1}:**
  - ➢ all-hadronic selection: ATLAS-CONF-2021-050 New
  - ➢ lepton+jets selection: Eur. Phys. J. C 79, 1028 (2019), ATLAS-CONF-2021-031
- **Interpreting the top-quark mass from boosted soft-drop jets using ATLAS MC**
  - ➢ Boosted ATLAS MC top vs NNL MSR top: ATL-PHYS-PUB-2021-034 New

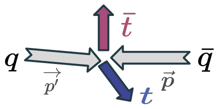
Top/anti-top charge asymmetry

tt charge asymmetry - Concept

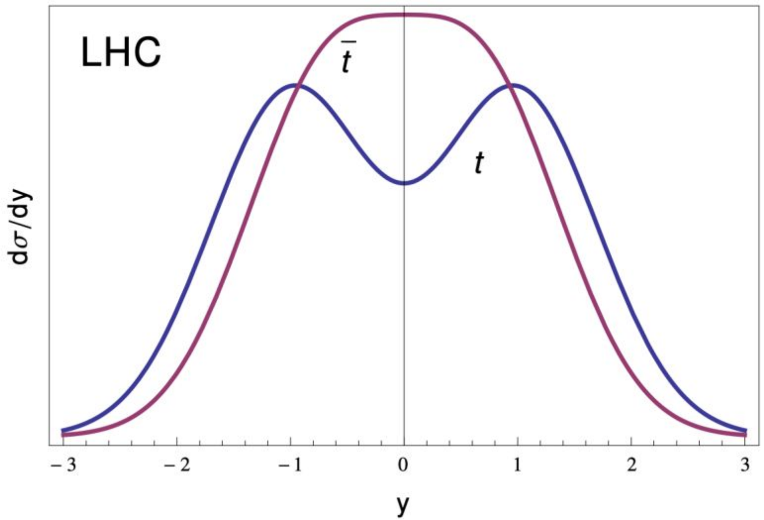
- The different probability for top and antitop quarks to be emitted in a considered phase-space region, is particularly sensitive to new physics.
- At LHC, anti-top tends to be produced more perpendicular to the beam axis than the top → **Charge asymmetry!**



$case\ 1 : Y(t) = 0, Y(\bar{t}) = 0$



$case\ 2 : Y(t) \neq 0, Y(\bar{t}) = 0$



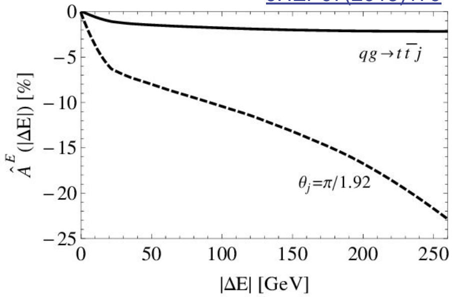
- Expected in SM:
  - Top produced preferentially in direction of q.
  - Anti-top produced preferentially in direction of anti-q.
  - Momentum imbalance of q and anti-q initial states.
- Probe charge asymmetry (A_c) @ATLAS by measuring:
  - **rapidity asymmetry in tt (NLO) production (A_y)** → $\Delta|y| = |y_t| - |y_{\bar{t}}|$
  - **Energy asymmetry in tt+j (LO) production (A_E)** → $\Delta E = E_t - E_{\bar{t}}$

$$A_Y = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

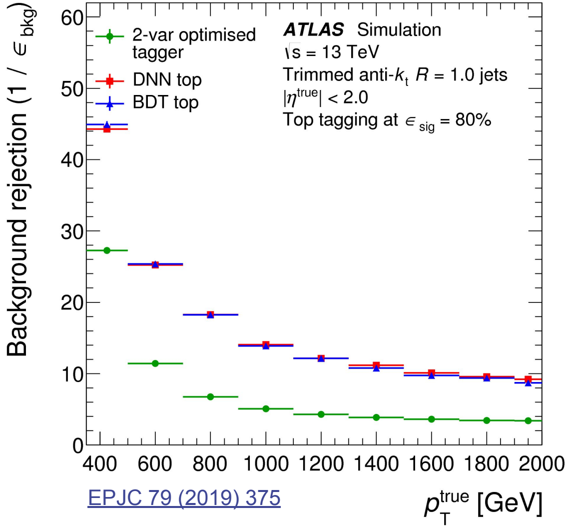
$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}$$

$$\sigma^{\text{opt}}(\theta_j) = \sigma(\theta_j|y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j|y_{t\bar{t}j} < 0)$$

tt charge asymmetry - Analysis Strategy



- Measurement in the **lepton+jets** channel in the **boosted topology.**
  - larger asymmetry value + easier to reconstruct than the resolved topology.
- The observed data is **unfolded** to particle level with the **Fully Bayesian Unfolding** (**FBU**) method.
- 1D and 2D **EFT limits** are obtained in a **χ2 fit** with simulated samples with **non-zero EFT coefficients.**
- Signal selection:
  - Leptonic top: tagged small-R jet associated to single lepton.
  - Boosted hadronic top: One Anti-kt R=1.0 trimmed jet
    - with p_T> 350 GeV.
    - with DNN 80% top-tagger. (12 jet substructure variables)
    - isolated from lepton.
  - Extra jet: p_T> 100 GeV. (energy asymmetry only)



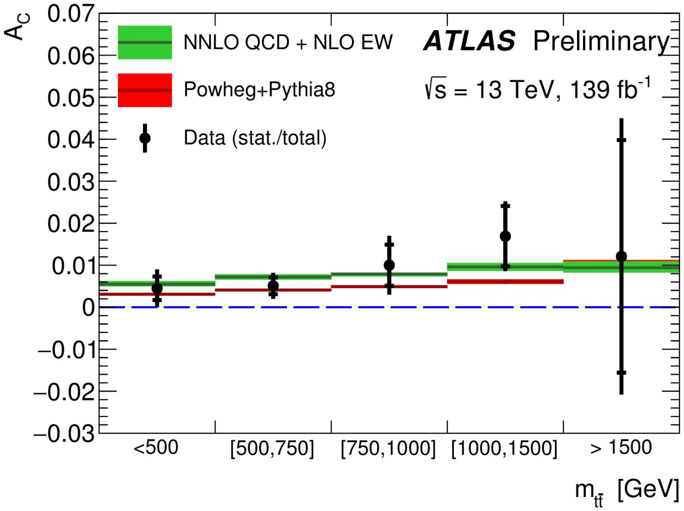
EPJC 79 (2019) 375

tt charge asymmetry - Results

Rapidity asymmetry

- Measured asymmetry differs from 0 by 4σ.
  - Consistent with SM simulation at NNLO.

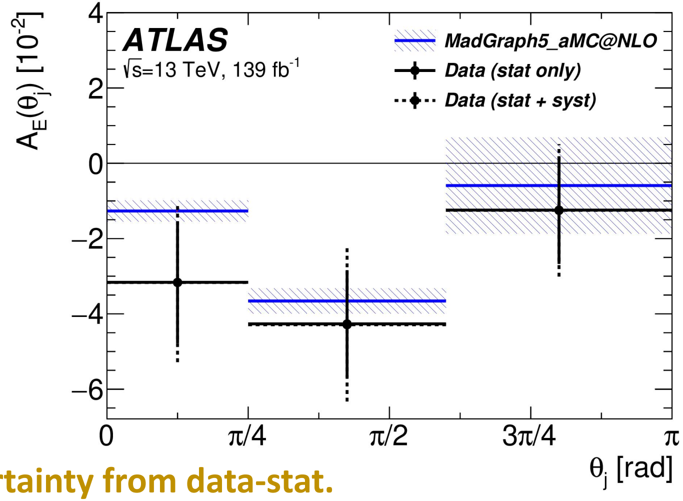
$$A_C = 0.0060 \pm 0.0015\text{(stat+syst.)}$$



Energy asymmetry

- Middle bin with with the largest **expected** asymmetry (2.1σ excess), where the jet is emitted perpendicular to the beam.

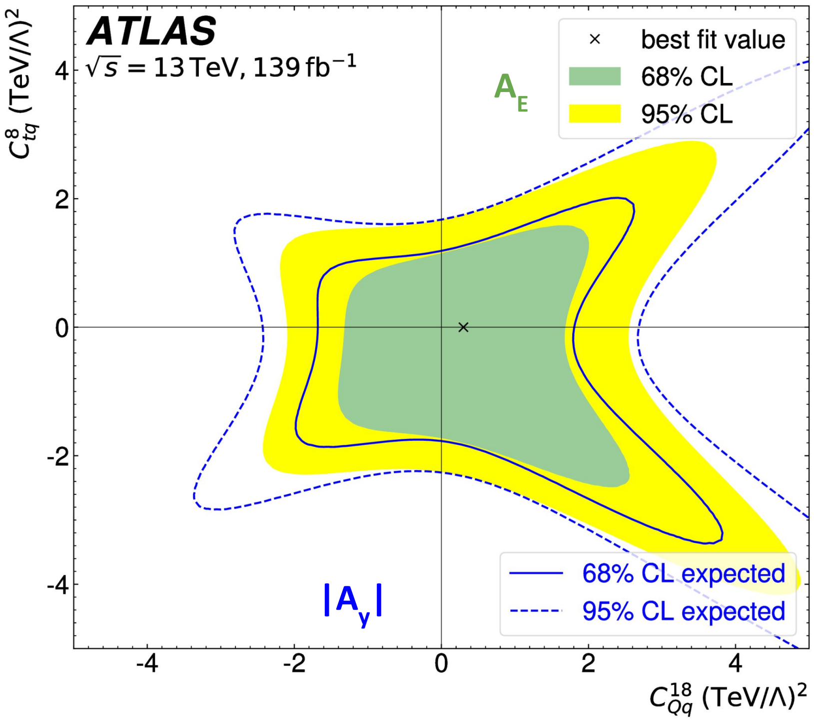
$$A_E^2 = -0.043 \pm 0.020$$



- **Largest uncertainty from data-stat.**
- **Largest systematic uncertainties from tt modelling.**

tt charge asymmetry - EFT interpretation

- Bounds on **Wilson coefficients (SMEFT)** from **energy vs rapidity** asymmetries.
- The QCD structure of the energy asymmetry is not the same as for the rapidity asymmetry in $t\bar{t}$ production.
- The two asymmetries probe **different directions** in **chiral** and **colour space**.
- Energy asymmetry is **complementary** to rapidity asymmetry and sensitive to the top-quark chirality in **4-quark EFT operators**.
- Energy asymmetry **resolves** remaining blind or nearly **blind directions** left by the rapidity asymmetry.
- **Combining** the energy and rapidity asymmetries in a joint fit would result in a better resolution of the Wilson coefficients.



tt differential cross sections

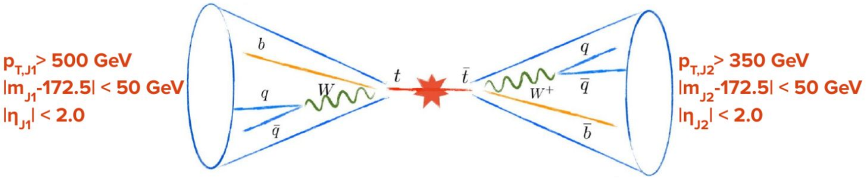
All hadronics vs. l+jets

tt differential cross sections - Analysis Strategy

- Measurement in the **lepton+jets and all hadronic** channels in the **boosted topology.**
- Background contribution is determined by a combination of Monte Carlo samples and data-driven techniques.
- The observed data is **unfolded** to particle and parton level (all hadronic only) with the **Iterative Bayesian Unfolding** method.
- 1D and 2D **EFT limits** are obtained in a **χ2 fit** with simulated samples with **non-zero EFT coefficients.**

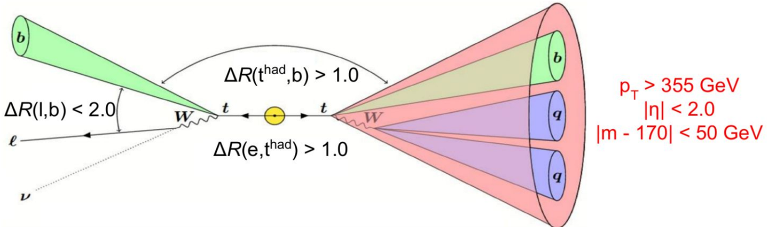
tt differential cross sections - Signal Selection

Hadronic event selection



- both top quarks boosted.
- Large-R jets: Anti-kt LCTopo R = 1:0 trimmed.
- Top-tagging: DNN top-tagger. (based on large-R jet substructure variables)
- B-tagging: Large-R jets matched to b-tagged track jets.

l+jets event selection



- Exactly one prompt lepton.
- One Large-R jet: with R = 1:0 reclustered from R = 0:4 anti-kt calo jets.
- At least two anti-kt R = 0:4 b-tagged jets.
- Missing energy: ETmiss > 20 GeV, ETmiss + ETW > 60 GeV.

tt differential cross sections - Background composition

Backround processes ordered by their contribution

Lepton+jets	**All-hadronic**
Single top	Multijet
$t\bar{t}$ +X(X=W,Z,H)	$t\bar{t}$ non-allhad
Multijet	Single-top
Others	$t\bar{t}$ +X(X=W,Z,H)

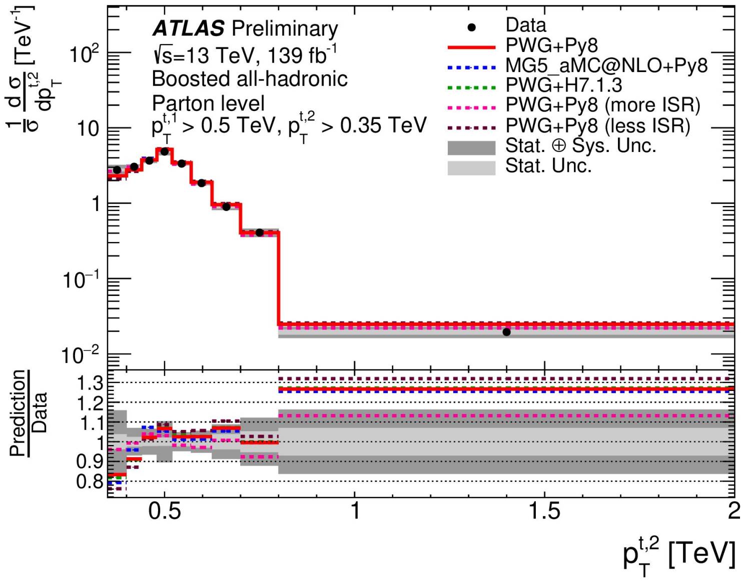
- **Multijet background** determined by data-driven techniques in both analyses: **Matrix method** (lepton+jets), **ABCD method** (all-hadronic).
  - Dominant in the all-hadronic measurement.
- **MC samples** used to determine other backgrounds contributions.
- **Wt single top** is a dominant background in lepton+jets measurement - special care needed due to ambiguity of Wt-channel definition.

ATLAS-CONF-2021-050

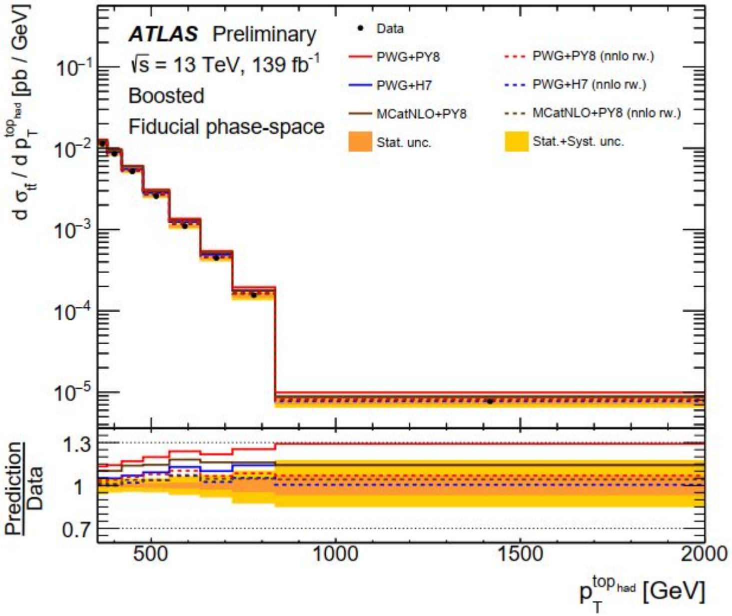
ATLAS-CONF-2021-031

tt differential cross sections - Results

Hadronic event selection



l+jets event selection



- Main uncertainties: Data statistics, JES, top-tagging.
- Variables sensitive to radiation show discrepancies between data and predictions.

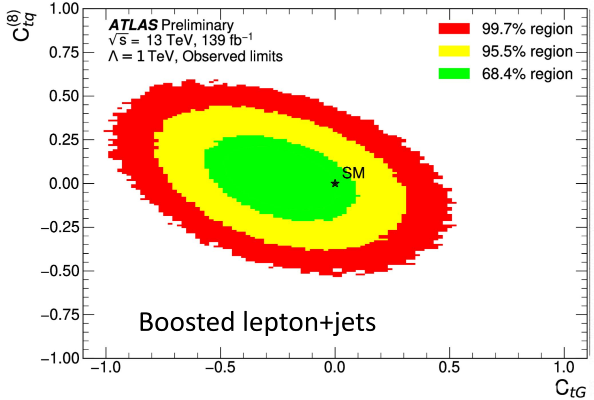
- Main uncertainties: Signal modeling.
- Significant reduction of jet energy scale uncertainties.
- MC overestimates data especially in high energy tails.

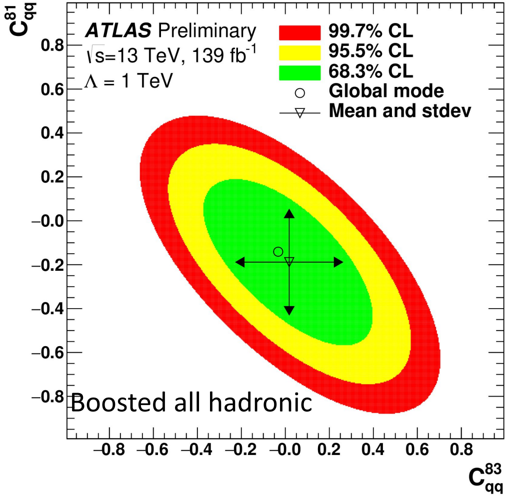
tt differential cross sections - EFT interpretation

ATLAS-CONF-2021-050

ATLAS-CONF-2021-031

- Boosted tops show good sensitivity to new physics.
- 2D CL limits determined for the selected LO EFT operators from the Warsaw basis.
  - 2 heavy-quark + 2 light-quark, 2 heavy quark + bosons operators.
- Top p_T used as a differential variable to fit the coefficients.
- Lepton+jets: SM-EFT interference terms only.
- All-hadronic: Both SM-EFT and EFT-EFT terms.
- Results compatible with SM only hypothesis.
- Observe no evidence for new physics but excellent sensitivity to $C^{(8)}_{tq}$.

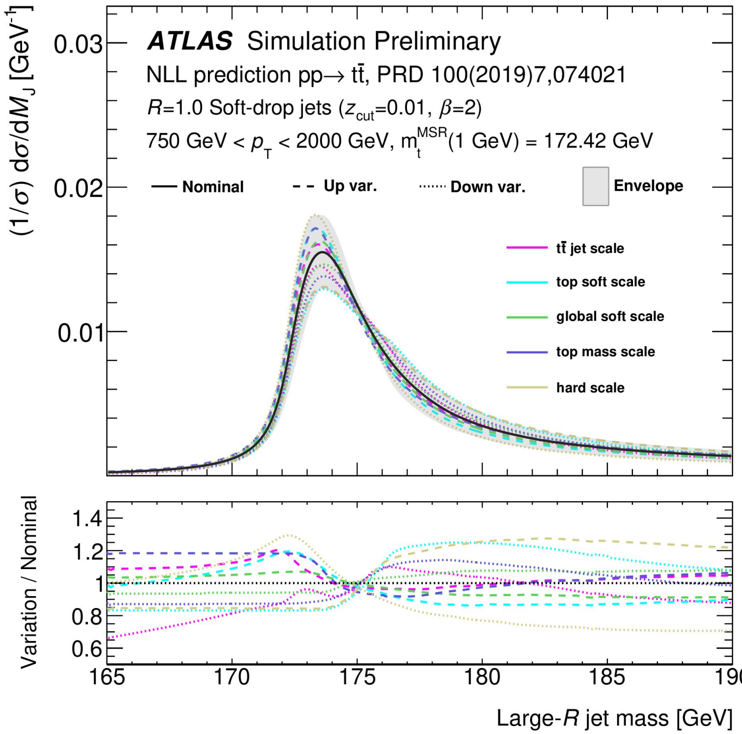




Top mass calibration

Top mass calibration - Analysis Strategy

- Compare boosted top-jet mass in ATLAS MC to top-jet mass from perturbative NLL theory jet calculation.
- Derive relation between MC top-quark mass and top mass in well-defined mass scheme (MSR) for highly boosted top events.
- NNL theory calculation available for top-quark mass w lightly groomed R=1.0 Soft-drop jets.
- Fit simulated jet mass distribution of boosted large-radius jets with NLL calculation at particle-level.
- Template fits for mass and two hadronization parameters in NLL theory.
- Simultaneous fit in three regions (before grooming).

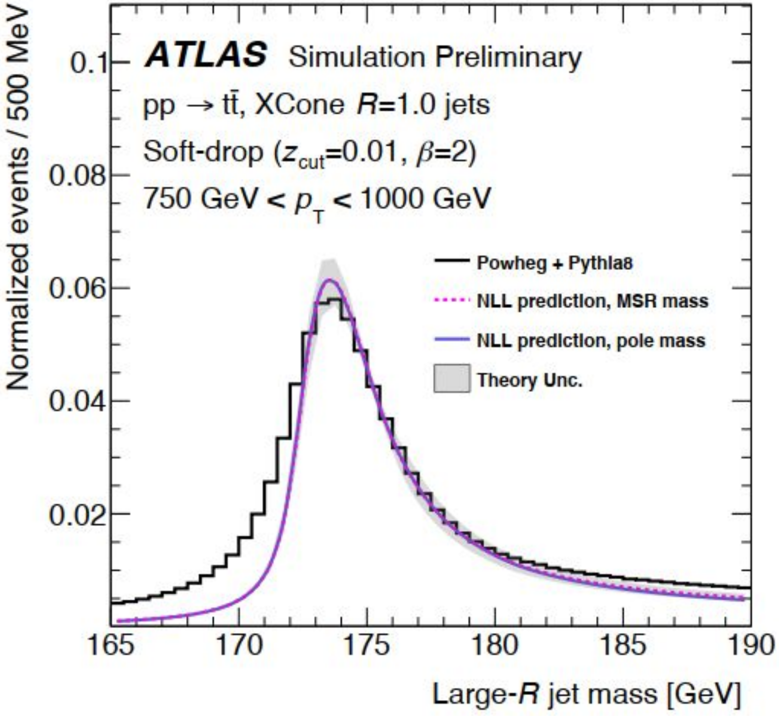


ATL-PHYS-PUB-2021-034

Top mass calibration - Results

- Extract relation between MC mass and MSR mass for boosted tops.
- Largest uncertainty from missing higher orders in NLL theory calculation.
- Will benefit greatly from improved theory calculations in the future.

$$m_t^{MC} = m_t^{MSR}(1\ GeV)\ + 80^{+350}_{-400}\ MeV$$



Conclusion

Conclusion

- Boosted top quarks have entered the precision regime.
- New results on top mass calibration, energy asymmetry, differential measurements: 3 papers, 5 CONF notes and 2 PUB notes this year (so far).
- All measurements in ATLAS consistent with the Standard Model predictions.
- No new physics observed but boosted topologies shown to be lucrative area to search.
- In the future, we'll be probing top quarks at even higher energy scales.

Back up