Boosting sensitivity in searches for heavy resonances with the ATLAS detector

CPAN 2023

Josu Cantero (UV/IFIC)

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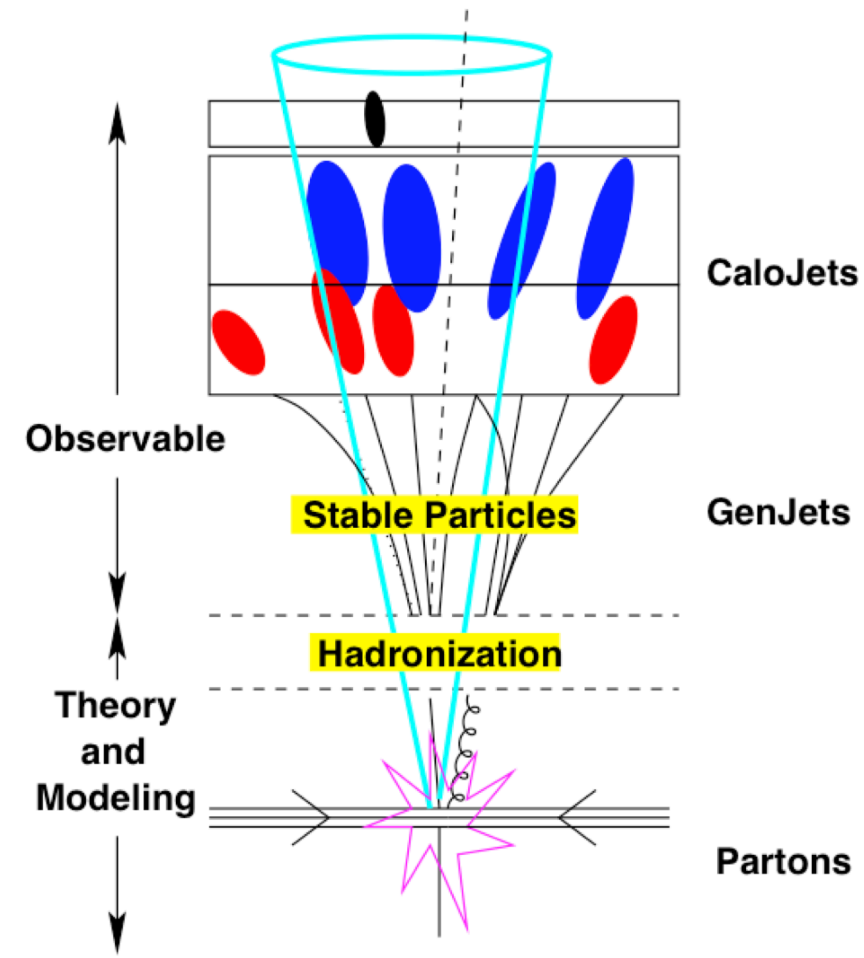
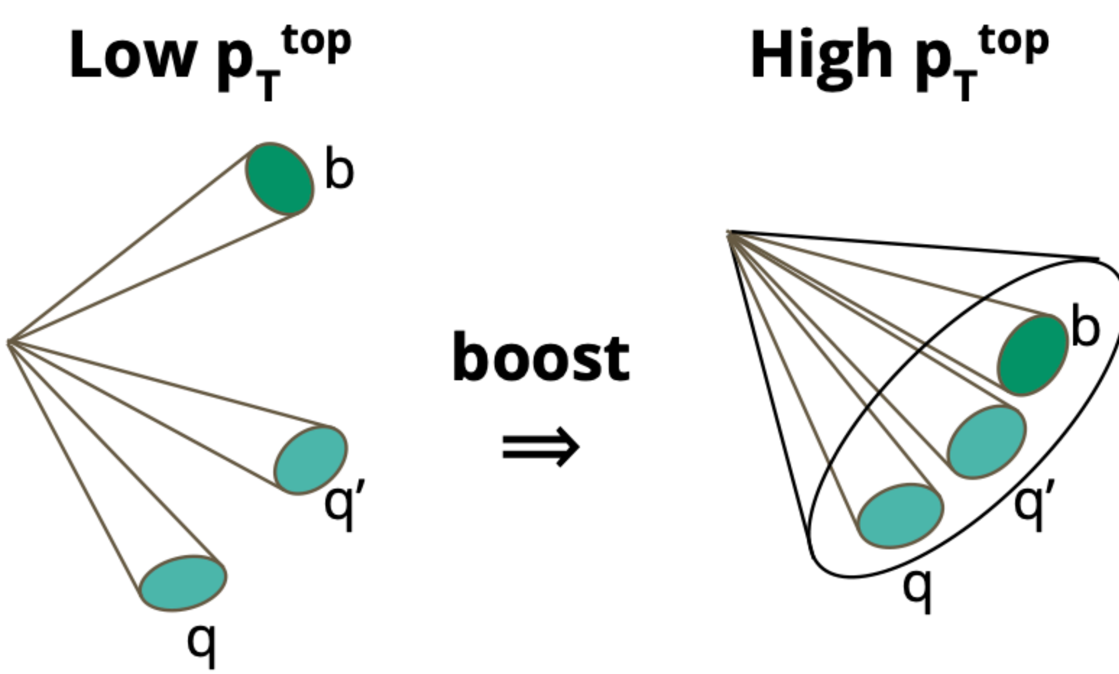
Introduction

- What is a jet?
  - Collimated bunches of stable particles.
  - Jets are reconstructed using jet algorithms
    - Sequencial Clustering algorithms: k_t, anti-k_t, CA.
    - These algorithms depend on one parameter: R (usually called jet radius)



- Jets are typically produced by light quarks/gluons created in the hard interaction or in hadronic decays of heavy resonances: $W, Z \to q\bar{q}$, $H \to b\bar{b}$, $t \to qq'b$.
  - If R sufficiently large, the decay products can be reconstructed in one jet: $R \sim 2m/p_{\mathrm{T}}$.
  - $R = 1$ is used in ATLAS.
    - The so-called large-R jets.



- Jet tagging strategy tries to identify which particle originated the jet using the information contained in the jet.
  - This is typically quantified by means of jet substructure variables.

Jet tagging

- Jet tagging very useful in searches including massive exotic resonances decaying into SM massive bosons or $t/\bar{t}$ quarks.
  - Extensively used nowadays in searches at LHC.
    - Higher $\sqrt{s}$ increases the fraction of boosted objects.
  - Increase signal sensitivity searching for massive exotic resonances.
    - High-p_{T} SM resonances reconstructed as single large-R jets.
  - Jet tagging to discriminate between signal-like final states and background where jets are originated from light quarks and gluons.

Phys. Rev. Lett 100 (2008) 242001

Jet substructure as a new Higgs search channel at the LHC

Jonathan M. Butterworth, Adam R. Davison
Department of Physics & Astronomy, University College London.

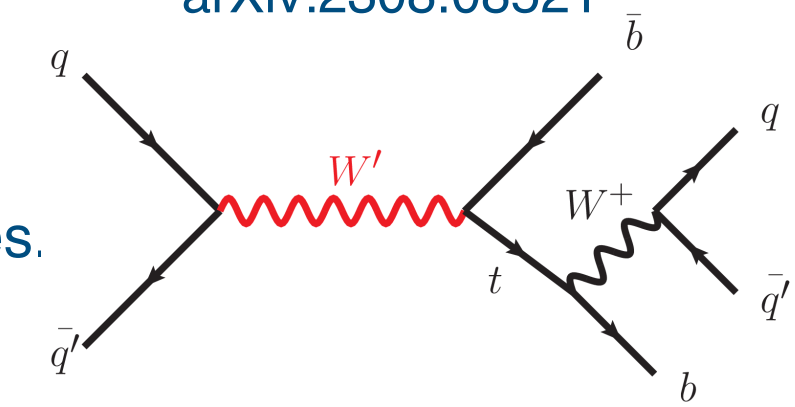
Mathieu Rubin, Gavin P. Salam
LPTHE; UPMC Univ. Paris 6; Univ. Denis Diderot; CNRS UMR 7589; Paris, France.

It is widely considered that, for Higgs boson searches at the Large Hadron Collider, WH and ZH production where the Higgs boson decays to $b\bar{b}$ are poor search channels due to large backgrounds. We show that at high transverse momenta, employing state-of-the-art jet reconstruction and decomposition techniques, these processes can be recovered as promising search channels for the standard model Higgs boson around 120 GeV in mass.

- Already proposed in 2008 to increase sensitivity of VH channel using $H \to b\bar{b}$ decays.

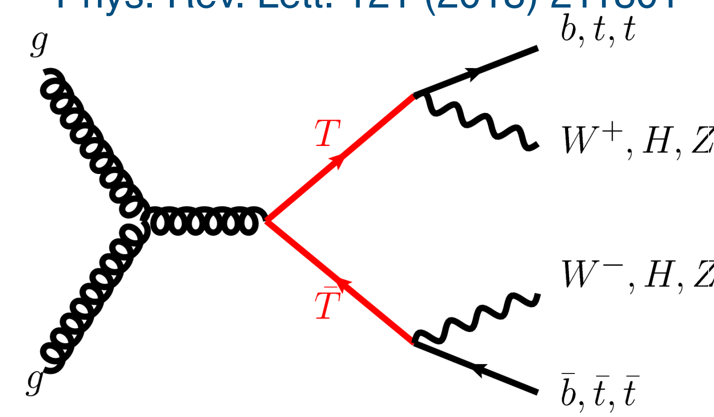
W' production

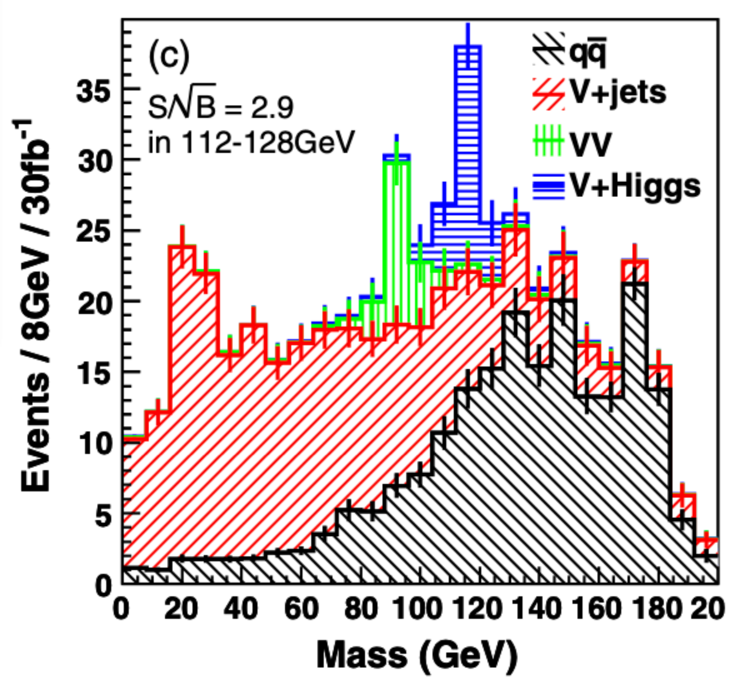
arXiv:2308.08521



VLQ production

Phys. Rev. Lett. 121 (2018) 211801

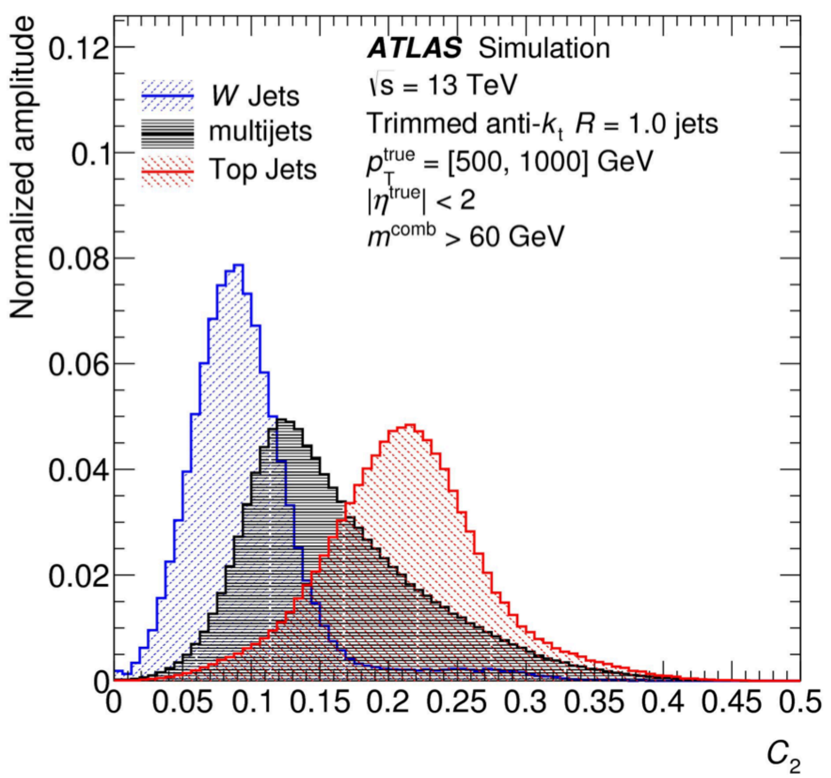


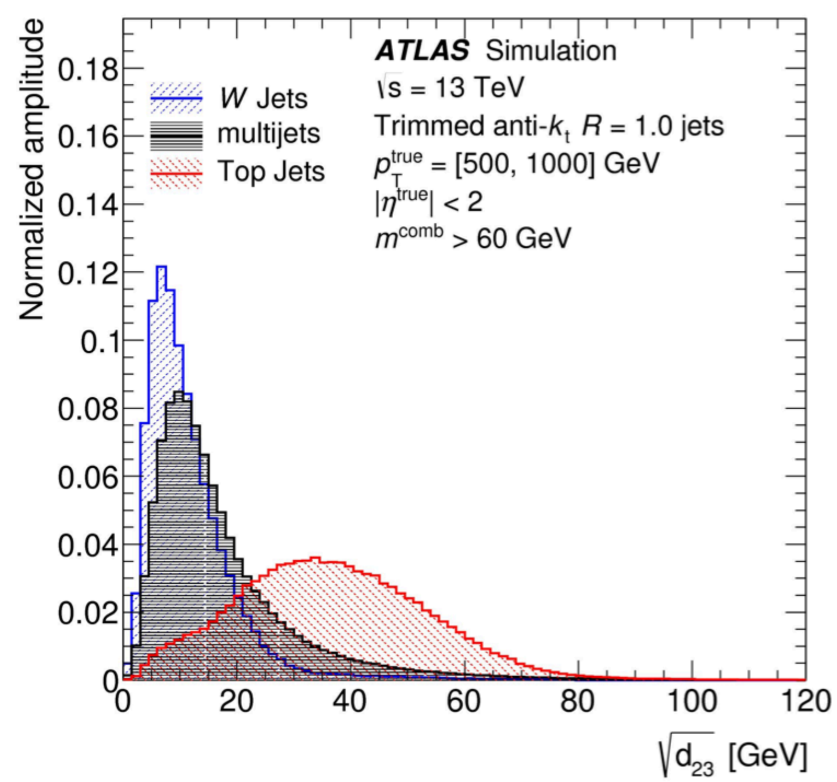


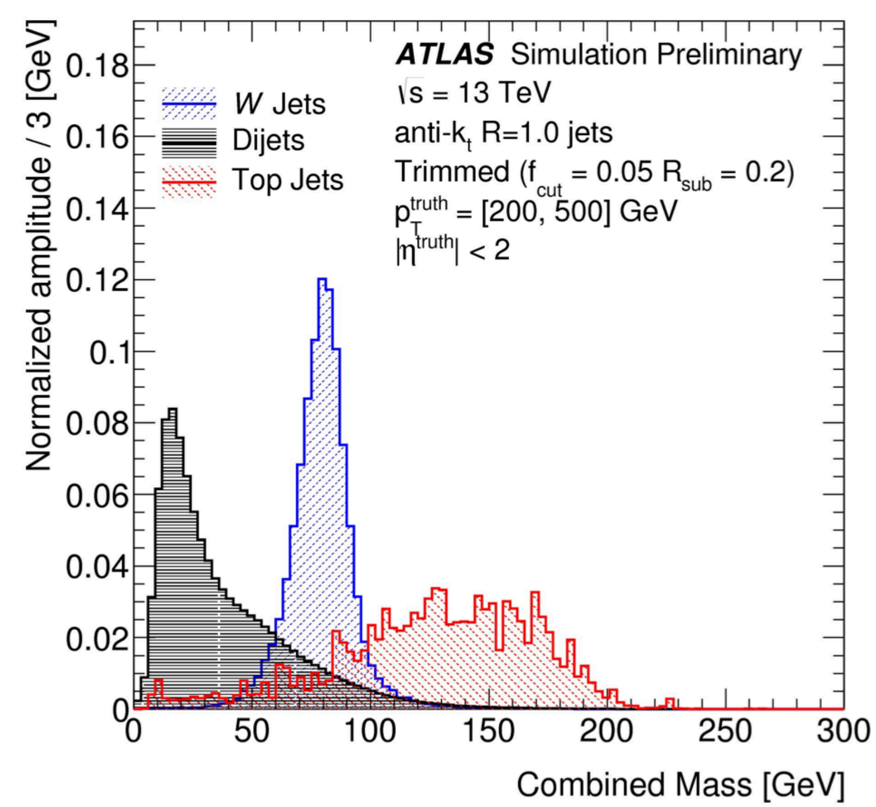
Jet substructure

- Jets originated from boosted resonances decay have distinctive substructure compared to jets originated from light quarks/gluons.
  - Sharp mass peaks/harder splitting scales.
  - Subjet multiplicity/b-tagging of large-R jet.
  - Color reconnection/Energy-Energy correlation variables.

Eur. Phys. J. C 79 (2019) 375







- Some jet substructure variables:
  - Splitting scales ($\sqrt{d_{12}}, \sqrt{d_{23}}$): scale of the 2→1 and 3→2 recombination step in a k_t clustering sequence.
  - Jet mass: distribution expected to peak at the resonance mass.
  - Energy-Energy correlators: weighted average of the angular moment of the energy deposits in a jet. Dimensionless C_2^β and D_2^β quite useful to identify two-body structure.

EECs:

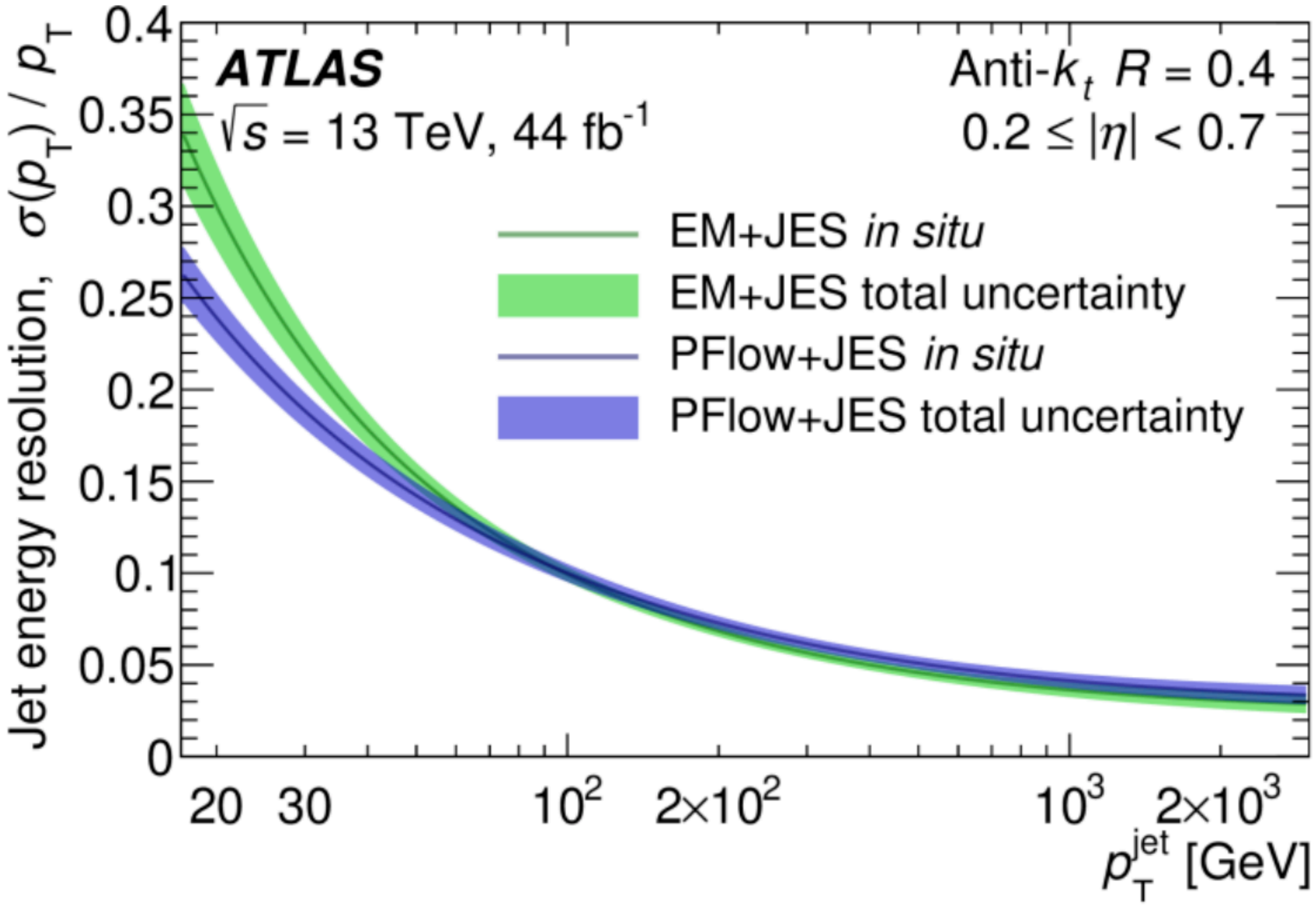
$$E_{CF0}(\beta) = 1,$$
$$E_{CF1}(\beta) = \sum_{i\in J} p_{T_i},$$
$$E_{CF2}(\beta) = \sum_{i<j\in J} p_{T_i} p_{T_j} \left(\Delta R_{ij}\right)^\beta,$$
$$E_{CF3}(\beta) = \sum_{i<j<k\in J} p_{T_i} p_{T_j} p_{T_k} \left(\Delta R_{ij}\Delta R_{ik}\Delta R_{jk}\right)^\beta$$

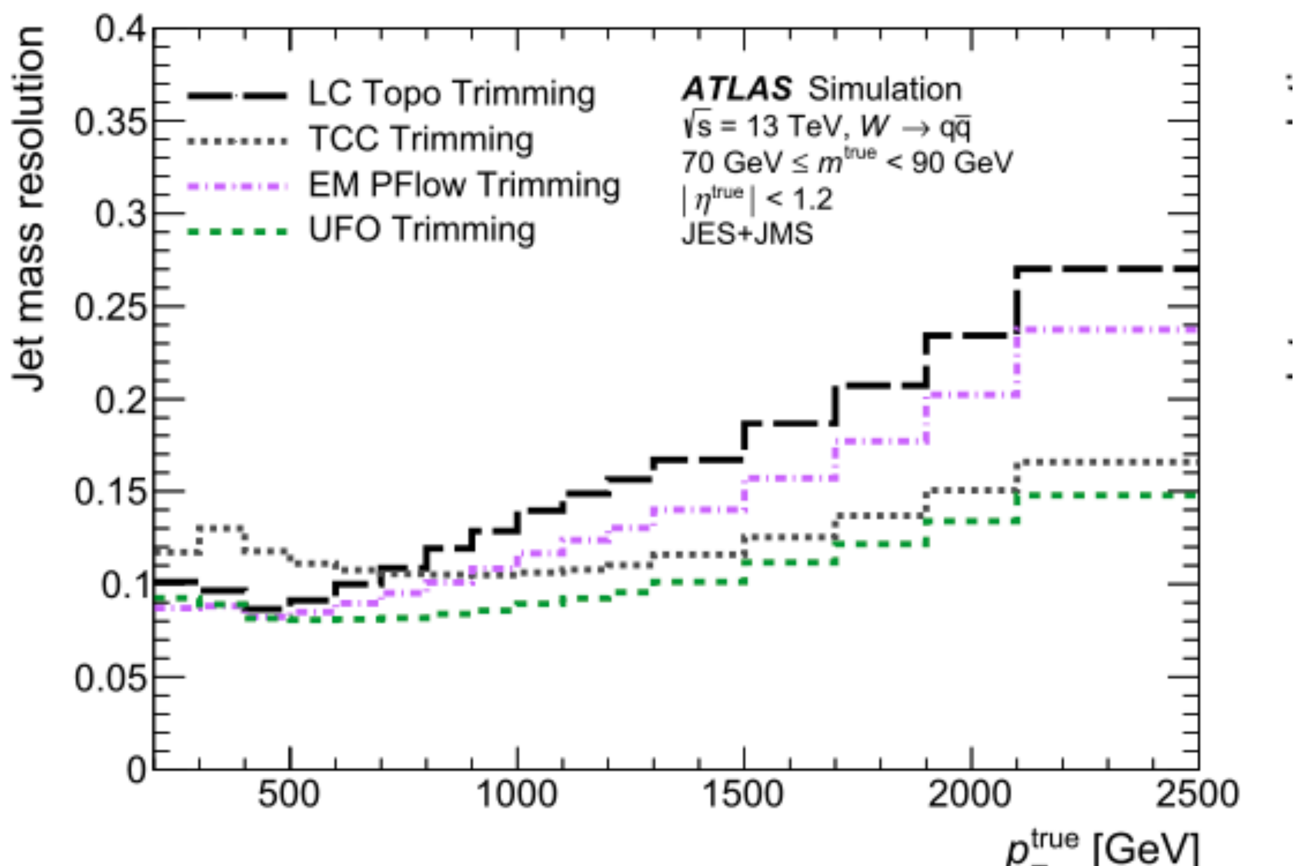
$$e_2^{(\beta)} = \frac{E_{CF2}(\beta)}{E_{CF1}(\beta)^2}, \quad e_3^{(\beta)} = \frac{E_{CF3}(\beta)}{E_{CF1}(\beta)^3}.$$

$$C_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^2}, \quad D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}.$$

Large-R jet collections

- From experimental point of view jet constituents can be defined in different ways:
  - LCTopo (Local Calibrated Topoclusters): 3D clusters of noise-suppressed calorimeter cells.
  - PFlow (Particle Flow Objetcts): combine tracking and calorimeter information.
    - Improve performance/pile-up stability for low pT jets. Eur. Phys. J. C 77 (2017) 466
    - High pT tracks excluded (worse energy resolution than clusters).
  - TCC (Track to Calo Cluster): tracking and calorimeter information combined in preference to tracking information (i.e η, ϕ information coming purely from tracks). ATL-PHYS-PUB-2017-015
    - Very good at high pT.
    - Use calorimeter energy scale and tracker spatial coordinates.
  - UFO (Unified Flow Objects): merge PFlow and TCC for better performance in a wider pT range. Eur. Phys. J. C 81 (2021) 334



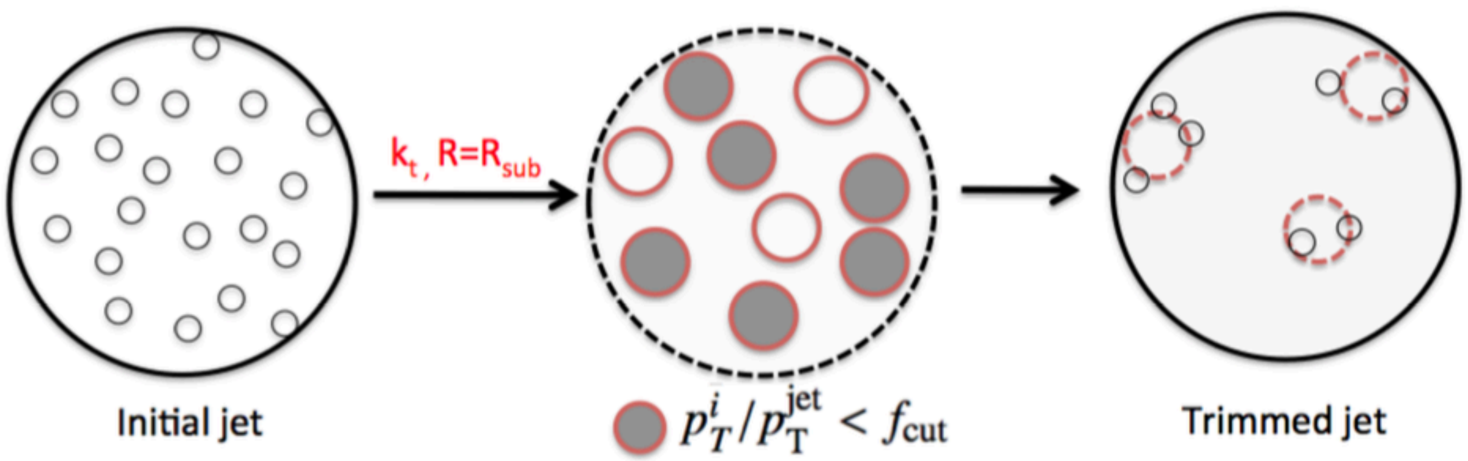


Large-R jet grooming

- Use to reduce sensitivity to pile-up and unrelated radiation.
  - Improve response ($O_{\mathrm{reco}}/O_{\mathrm{truth}}$) and pile-up stability of jet substructure variables.
- Several groomers in the market.
  - Trimming and SoftDrop used in ATLAS.

Trimming

- Remove low-pT contributions at the subjet level.



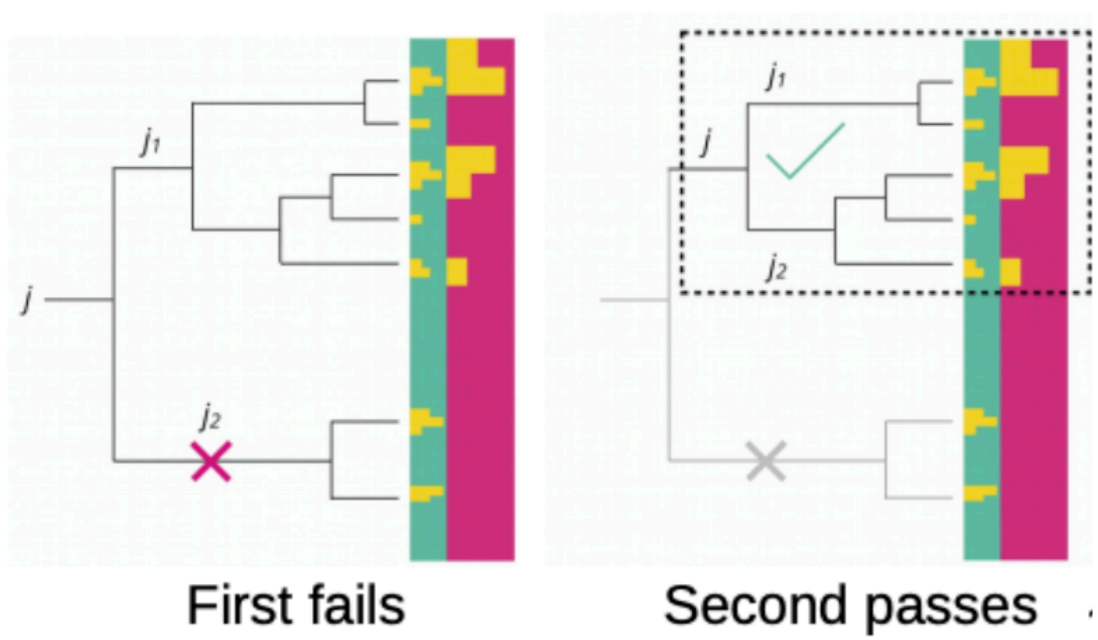
Soft-Drop

- Define splittings using CA declustering.
- Apply SoftDrop:
  - Start from first jet splitting.
  - Reach passing condition for both splittings.

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{cut}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

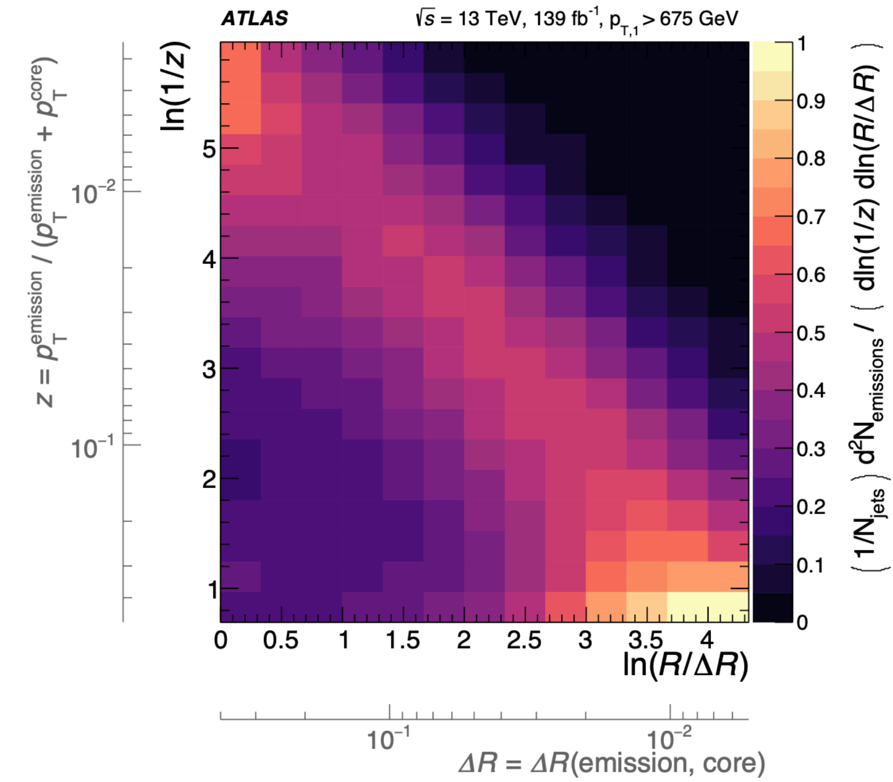
→ Keep both

→ "Drop" constituent



Jet tagging techniques

Phys. Rev. Lett. 124 (2020) 222002



- There are different ways to build a tagger.
  - Moment-based taggers:
    - Identify jet substructure moments with good separation power and apply cuts on them.
      - This can be done sequentially: 3-var W/Z tagger.
      - On a NN score: ANN W/Z tagger, DNN top tagger.
  - Declustering taggers:
    - Attempt to reconstruct the shower history of the jet.
      - Shower deconstruction: quantify if jet declustering is signal or background like: SD top tagger.
      - Lund plane based taggers: use Lund-plane information to discriminate between signal and background jets.
        - NNs allow to do it quite efficiently i.e GNNs
  - Constituent based taggers:
    - Use jet constituent information to feed a NN to discriminate between signal and bkg jets.
      - Large number of parameters is typically needed.

arXiv:1902.09914

	AUC	Acc	$1/\epsilon_B$ ($\epsilon_S = 0.3$) single	mean	median	#Param
CNN [16]	0.981	0.930	914±14	995±15	975±18	610k
ResNeXt [31]	0.984	0.936	1122±47	1270±28	1286±31	1.46M
TopoDNN [18]	0.972	0.916	295±5	382± 5	378 ± 8	59k
Multi-body N-subjettiness 6 [24]	0.979	0.922	792±18	798±12	808±13	57k
Multi-body N-subjettiness 8 [24]	0.981	0.929	867±15	918±20	926±18	58k
TreeNiN [43]	0.982	0.933	1025±11	1202±23	1188±24	34k
P-CNN	0.980	0.930	732±24	845±13	834±14	348k
ParticleNet [47]	0.985	0.938	1298±46	1412±45	1393±41	498k
LBN [19]	0.981	0.931	836±17	859±67	966±20	705k
LoLa [22]	0.980	0.929	722±17	768±11	765±11	127k
LDA [54]	0.955	0.892	151±0.4	151.5±0.5	151.7±0.4	184k
Energy Flow Polynomials [21]	0.980	0.932	384			1k
Energy Flow Network [23]	0.979	0.927	633±31	729±13	726±11	82k
Particle Flow Network [23]	0.982	0.932	891±18	1063±21	1052±29	82k
GoaT	0.985	0.939	1368±140		1549±208	35k

Jet tagging techniques

- Trimmed LCTopo Large-R jets taggers
  - 3-variable based W and Z taggers: D_2, N_{trk} and m_{jet}^{comb}.
    - Also available for TCC Large-R jets.
  - DNN top taggers: based on jet moments.
  - Xbb tagger: b-tagging info from three leading VR-trackjets feeding a NN.

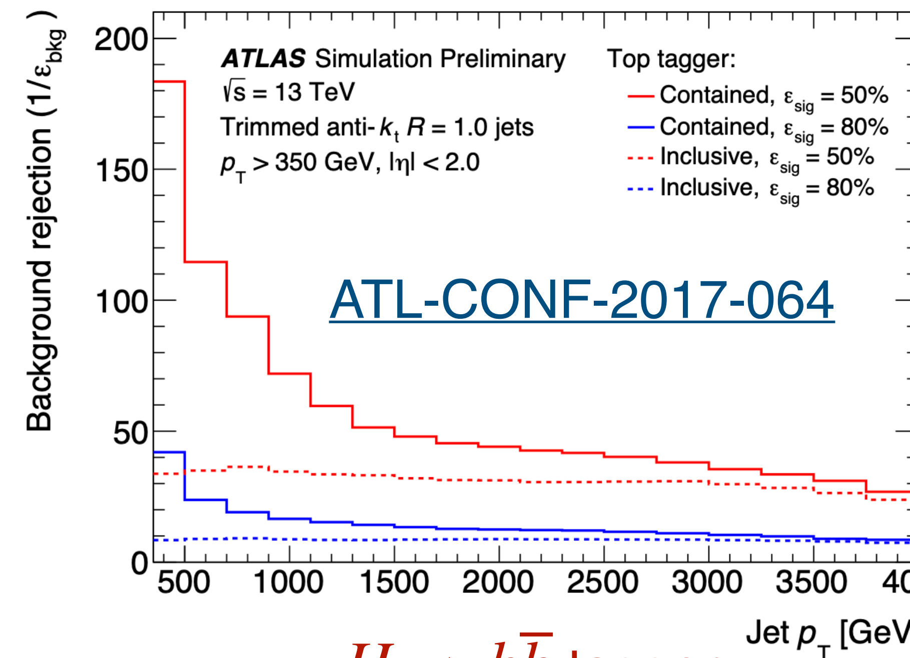
50% and 80% flat signal efficiency WPs defined

Inputs to DNN top tagger

Observable	Variable	Used for
Calibrated jet kinematics	p_T, m^{comb}	top,W
Energy correlation ratios	e_3,C_2,D_2	top,W
N-subjettiness	τ_1,τ_2,τ_{21}	top, W
	τ_3,τ_{32}	top
Fox–Wolfram moment	R_2^{FW}	W
Splitting measures	z_{cut}	W
	$\sqrt{d_{12}}$	top, W
	$\sqrt{d_{23}}$	top
Planar flow	$\mathcal{P}$	W
Angularity	a_3	W
Aplanarity	A	W
KtDR	$KtDR$	W
Qw	Q_w	top

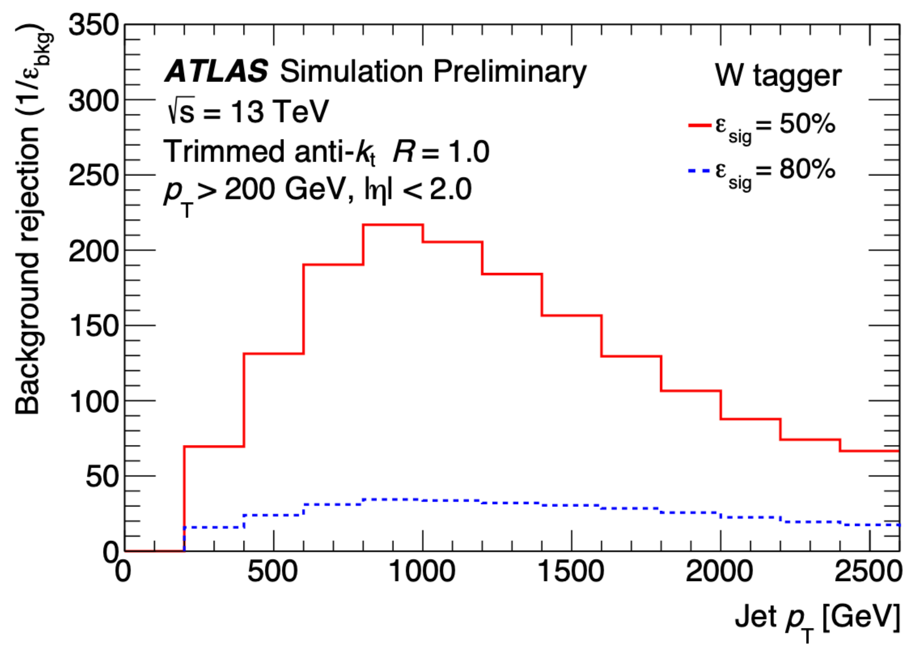
$$D_{Xbb} = \ln \frac{p_{Higgs}}{f_{top} \cdot p_{top} + (1 - f_{top}) \cdot p_{multijet}}$$

Top tagger



ATL-CONF-2017-064

W tagger



$H \rightarrow b\bar{b}$ tagger

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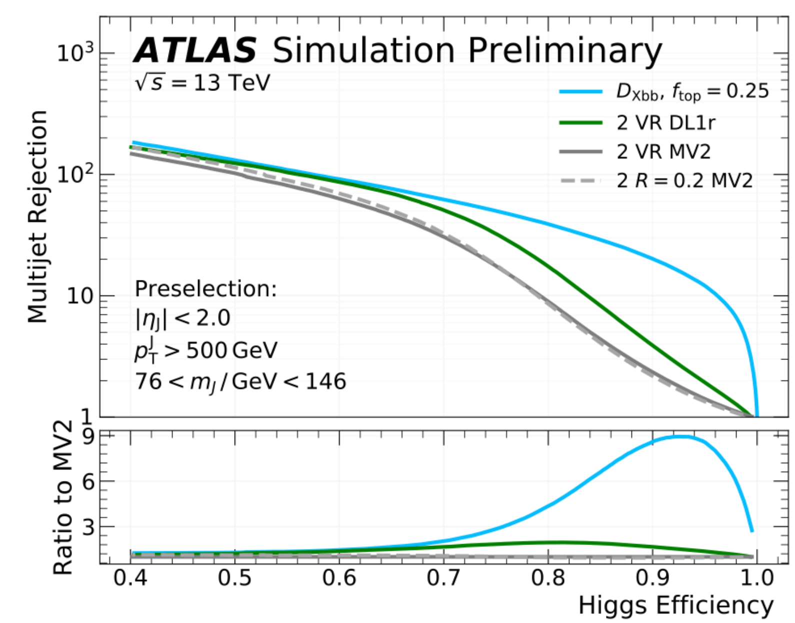
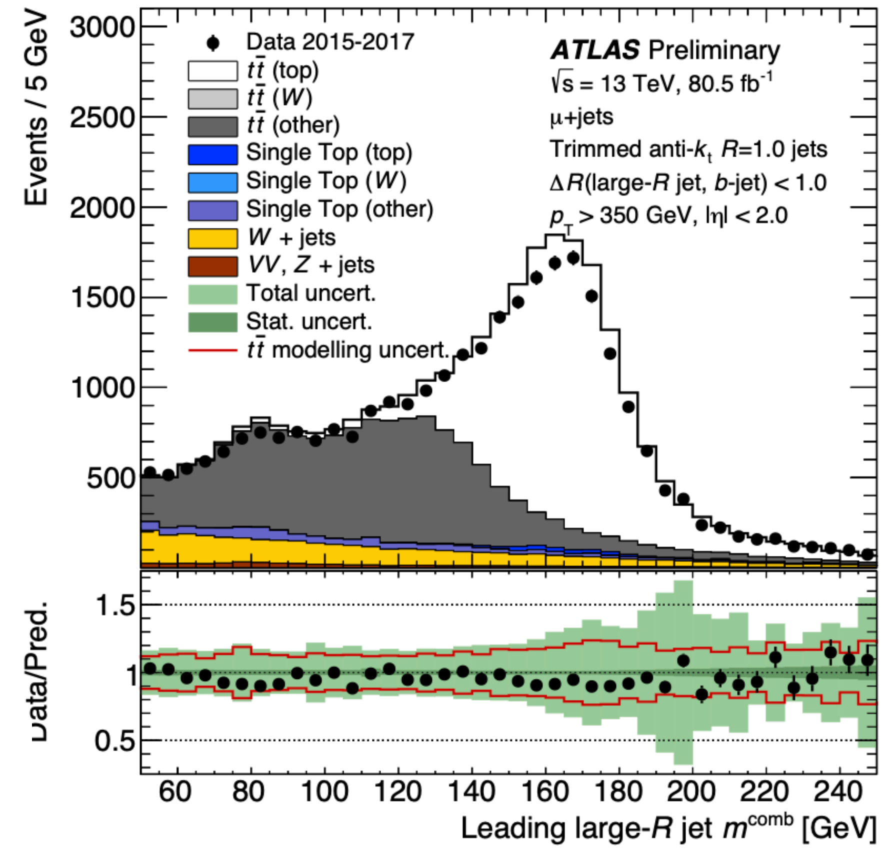


Jet tagging techniques

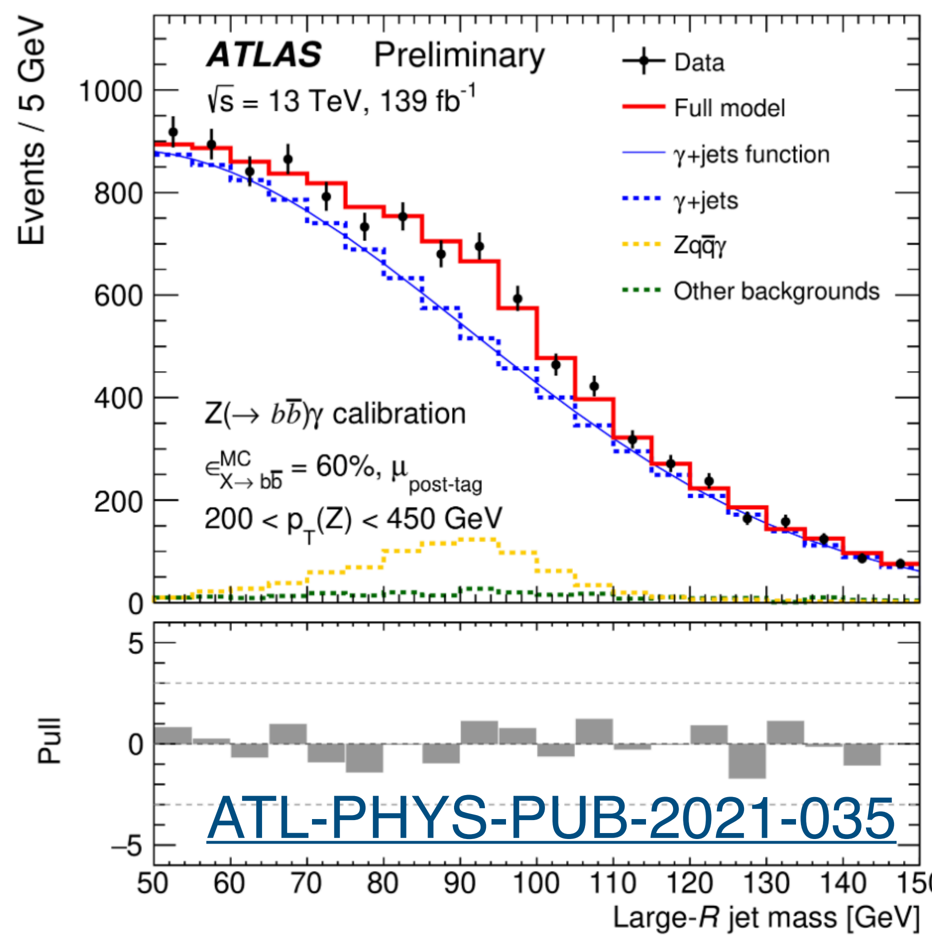
- Differences between data and MC on jet substructure lead to differences on jet tagging performance
  - Taggers need to be calibrated!
  - Calibration is done by means of Scale Factors (SFs).
    - The MC efficiency is corrected to data efficiency: $SF_{\text{eff}}(p_{\text{T}}) = \epsilon_{\text{data}}/\epsilon_{\text{MC}}$.
      - Inefficiency SFs are needed to maintain unitarity: $SF_{\text{ineff}}(p_{\text{T}}) = (1 - SF_{\text{eff}} \cdot \epsilon_{\text{MC}})/(1 - \epsilon_{\text{MC}})$

- Semileptonic $t\bar{t}$ events to estimate the SFs for top and W taggers.
- $Z \to b\bar{b}$, $g \to b\bar{b}$ and semileptonic $t\bar{t}$ for Xbb tagger.
- Multijet and γ+jets events for background SFs in 200 GeV $\lesssim p_T \lesssim$ 3 TeV.
- MC based high-p_{T} extrapolation uncertainties

ATL-PHYS-PUB-2020-017

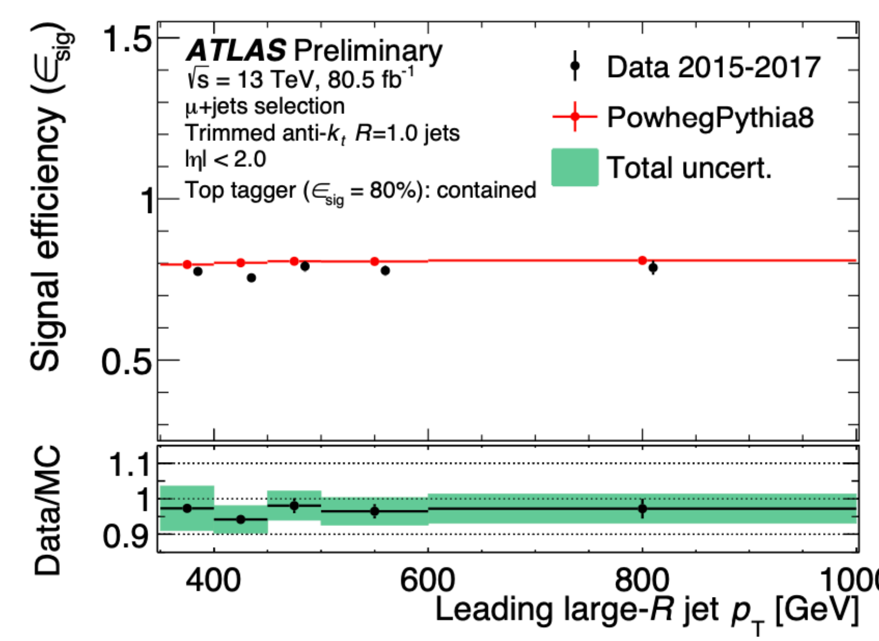


Xbb tagger 60% WP



ATL-PHYS-PUB-2021-035

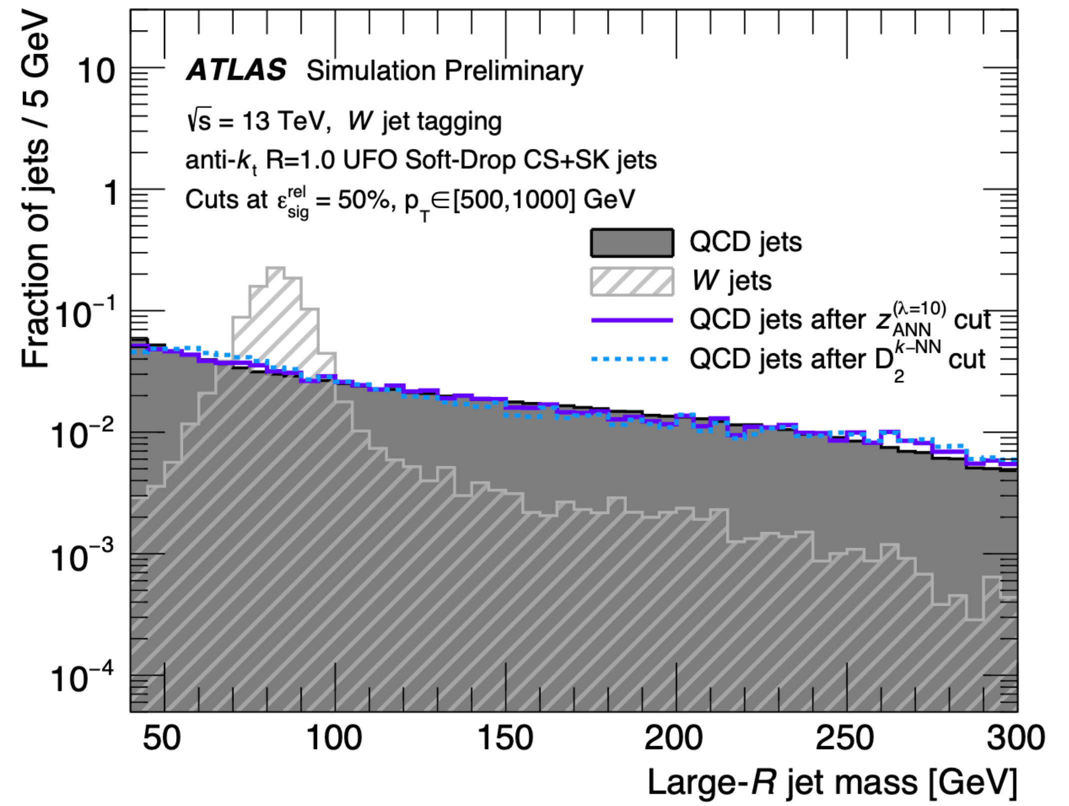
Top tagger 80% WP



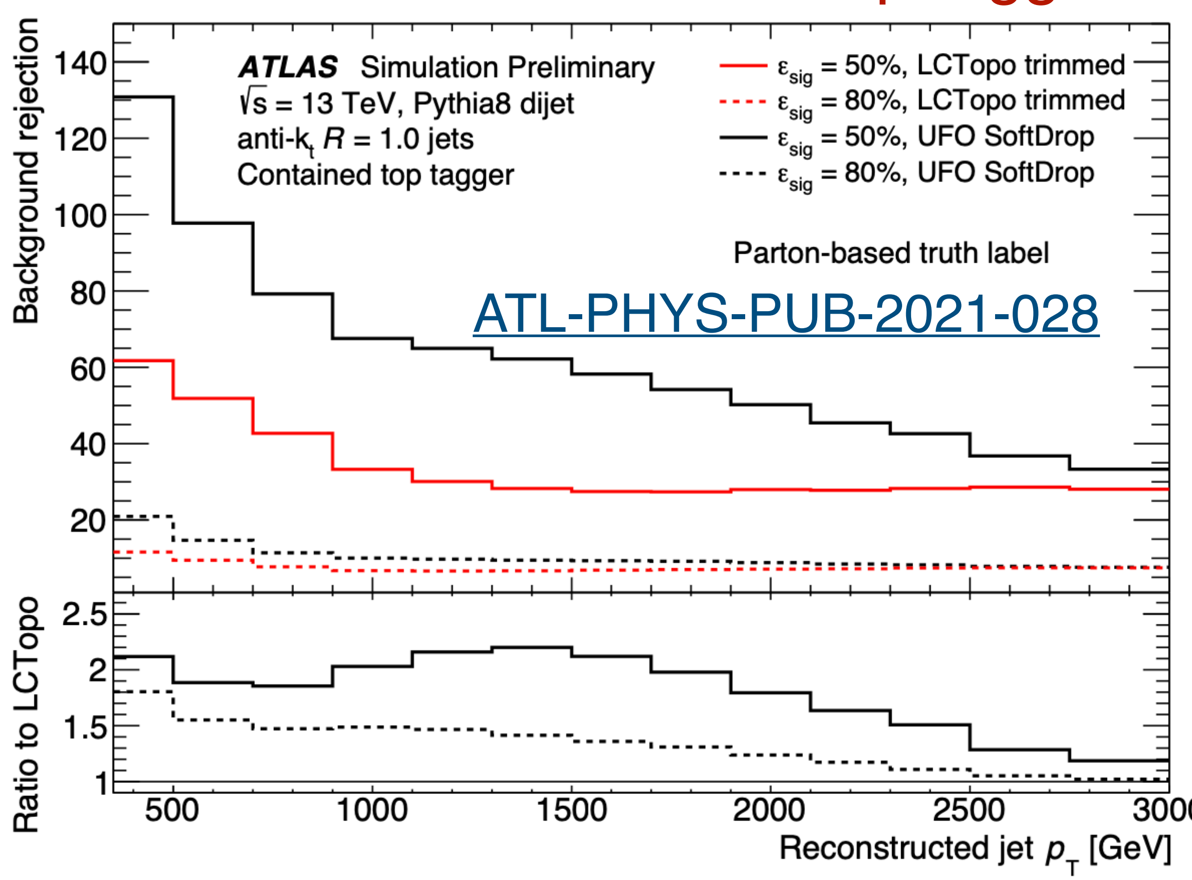
Jet tagging techniques

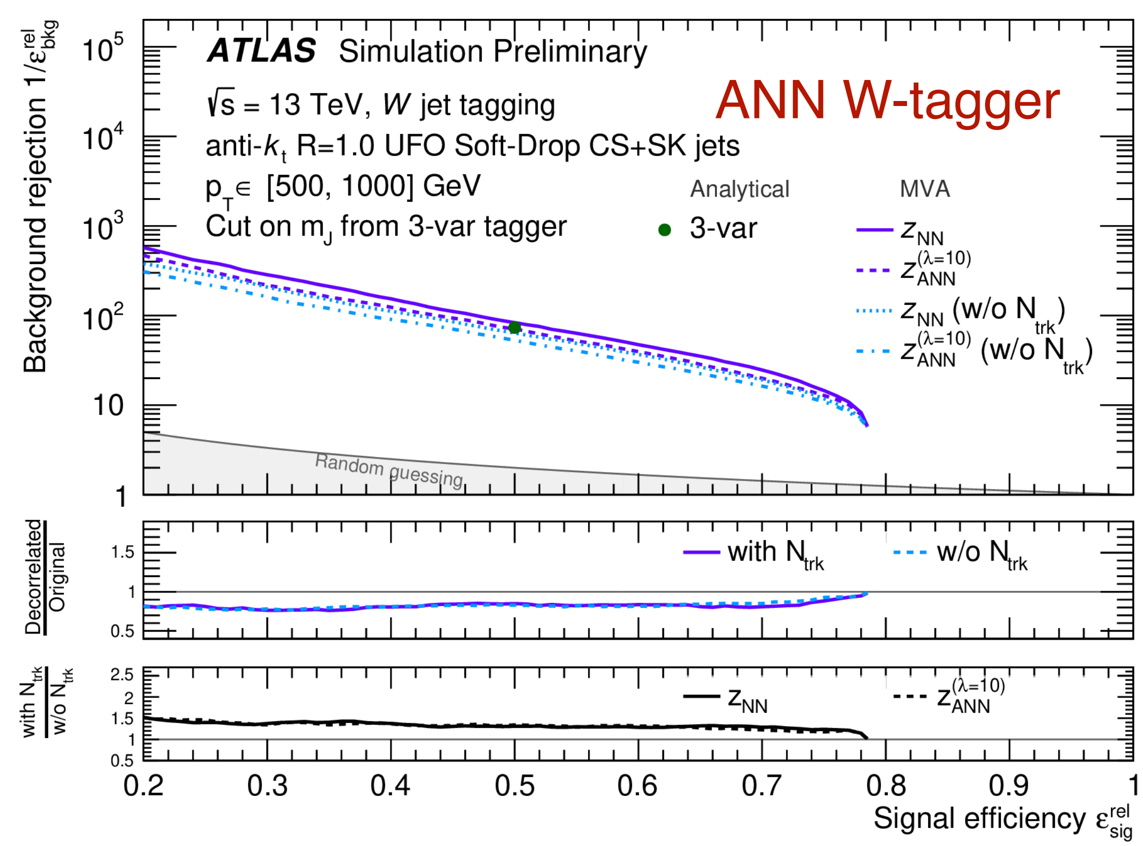
- SD CS+SK UFO Large-R jets.
  - 3-variable based W and Z taggers: D_2, N_{trk} and $m_{\text{jet}}^{\text{UFO}}$.
  - ANN W/Z tagger:
    - decorrelating tagger score and $m_{\text{jet}}^{\text{UFO}}$.
    - Based on jet moments.
  - Contained and inclusive DNN top taggers.
    - Optimisation of jet moments with respect to previous version.

ANN W-tagger ATL-PHYS-PUB-2021-029



Top tagger

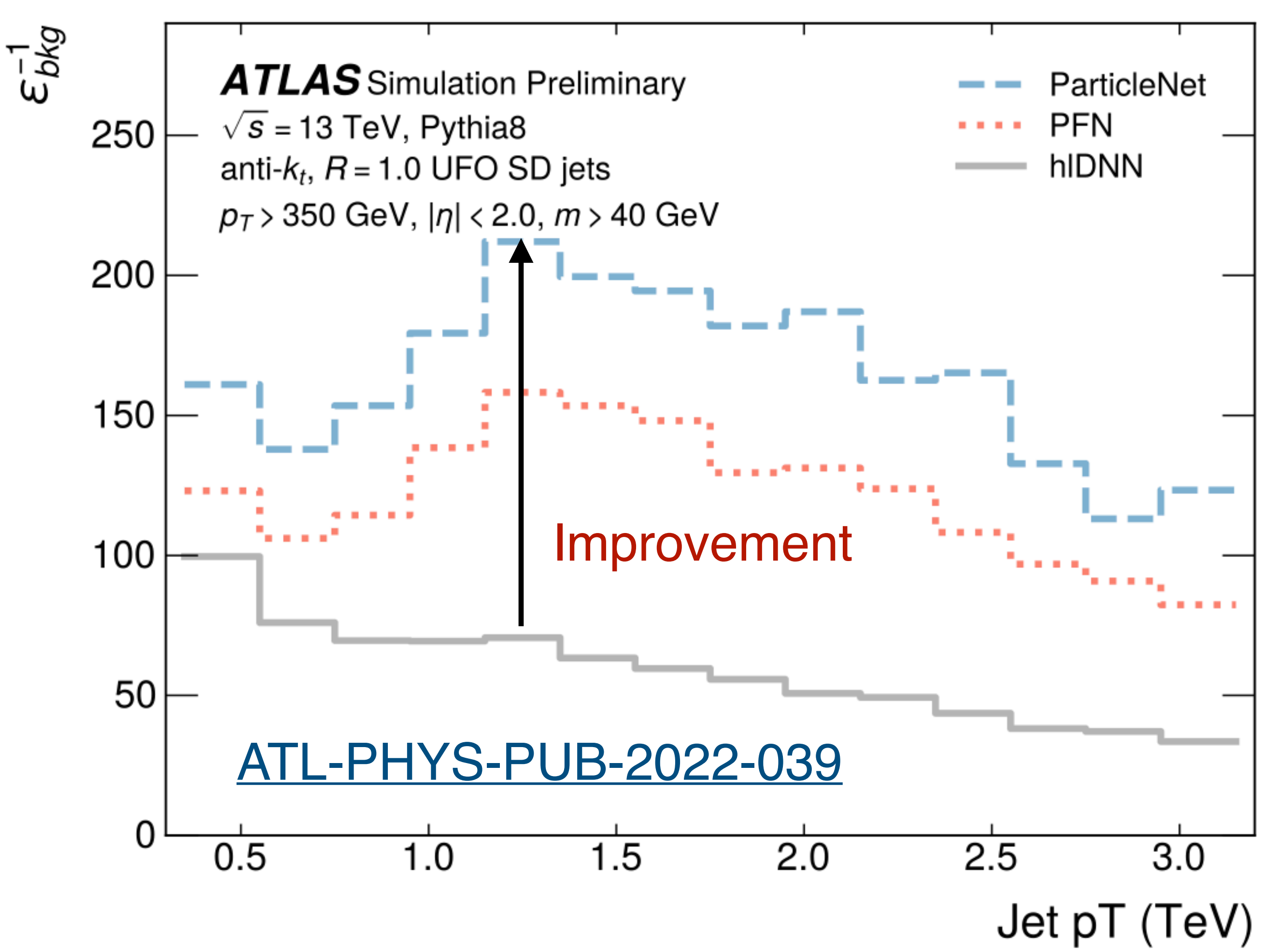




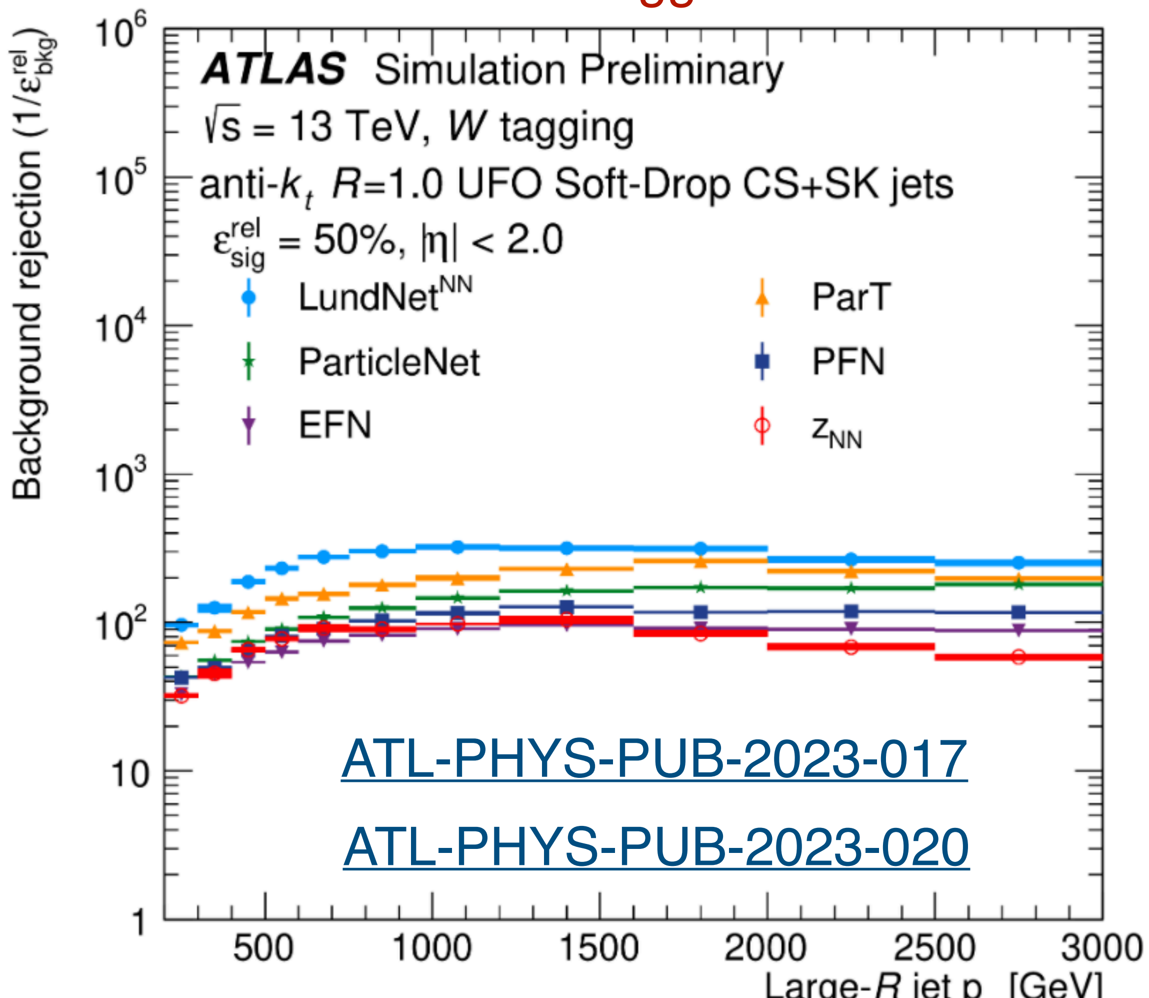
Jet tagging techniques

- Huge effort to derive taggers based on low level quantities.
  - All jet information is contained in the constituents.
  - Feed NNs with constituents to increase the performance?
    - Modern architectures help on this task: GNN, Transformers …
    - Physics wise quantities replaced by powerful NNs?
      - Blackbox: difficult to understand which physics the NN is learning.

ParticleNet top tagger



W tagger

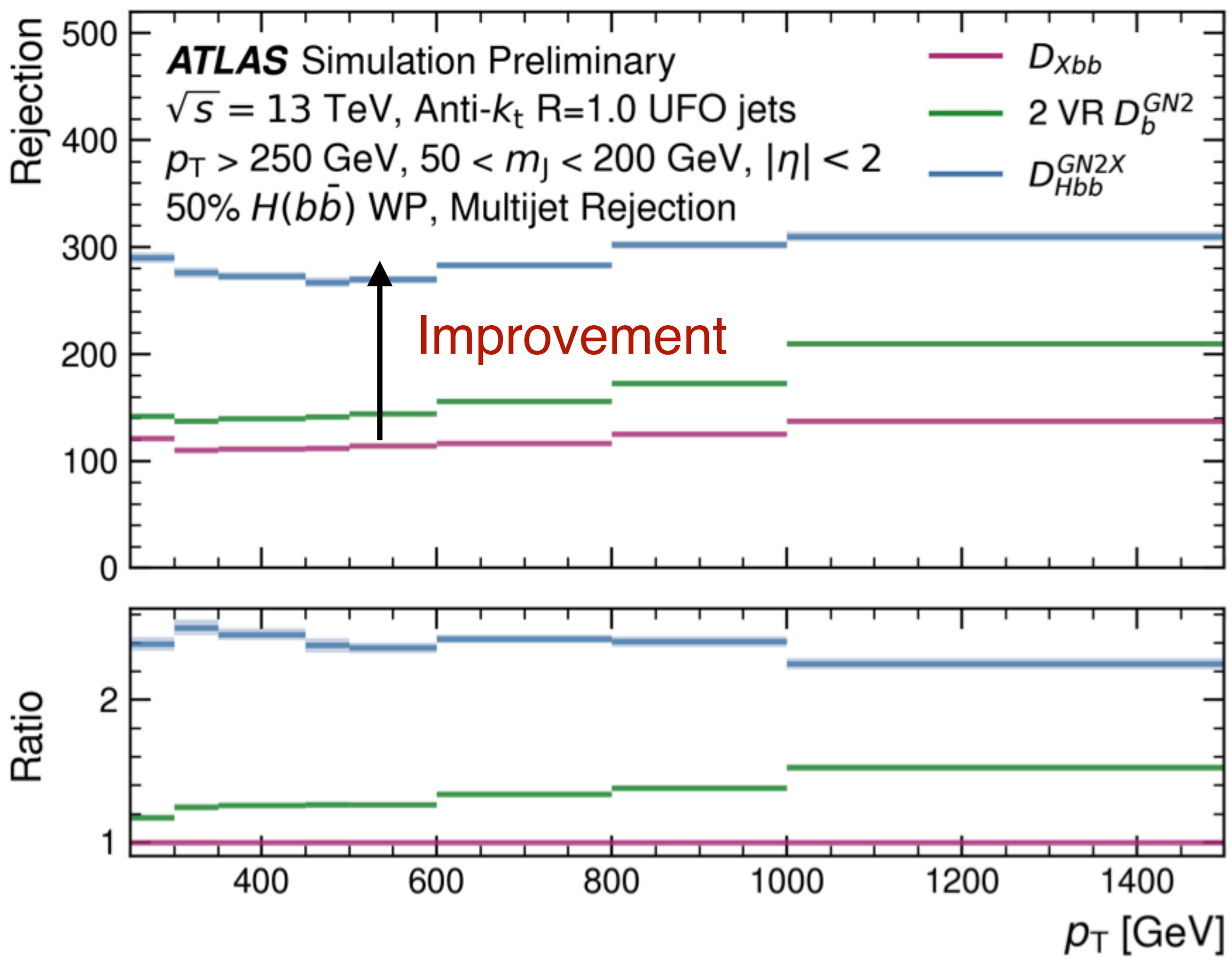


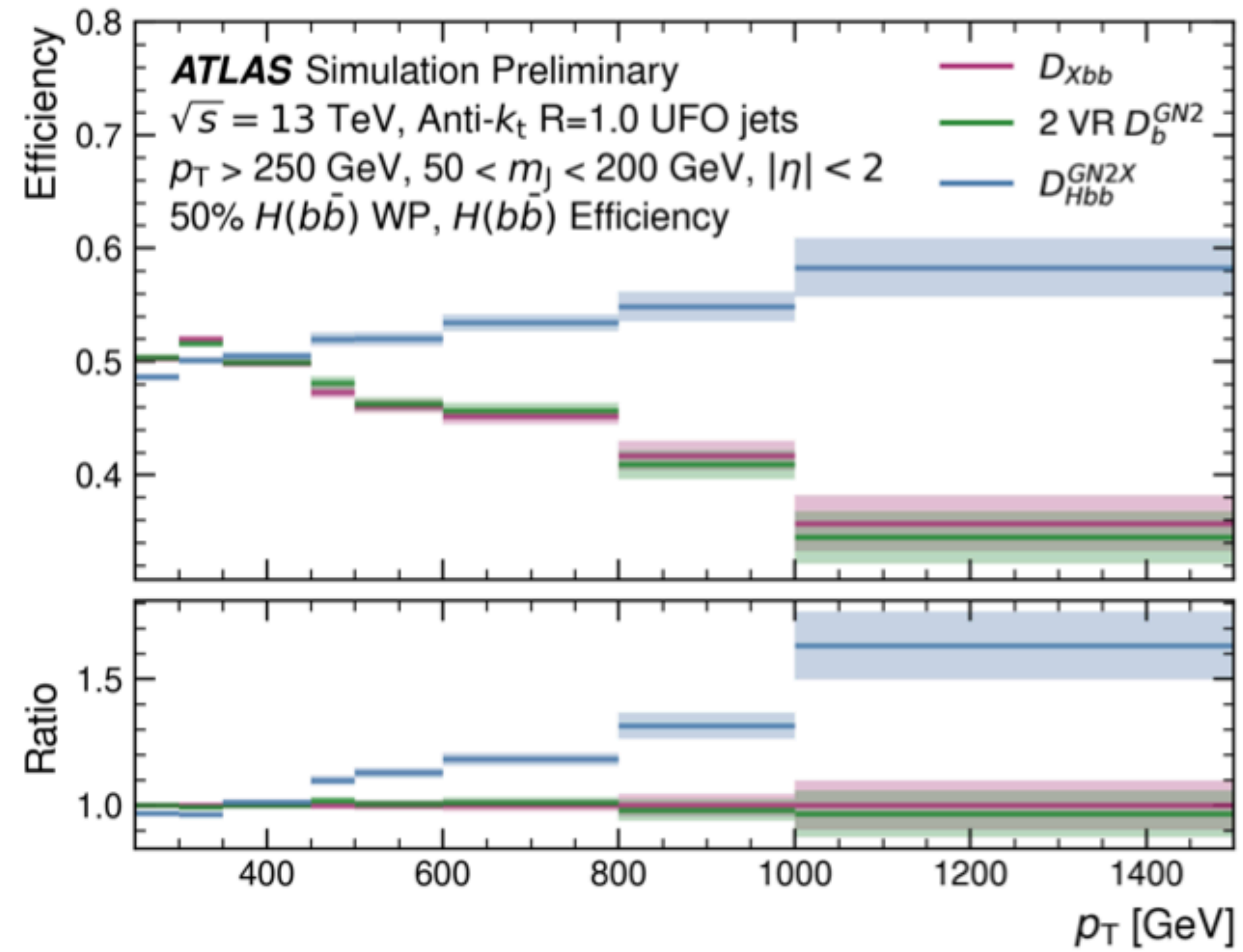
- GNNs including Lund-plane information best performance W tagger.
  - Physics motivated inputs → How the information is sorted still matters!

Jet tagging techniques

- Similarly, including all available tracking information beneficial for $H \to b\bar{b}$ tagger.
  - p_{T}, mass of the jet, impact parameters, number of hits in different ID layers of associated tracks
  - All these information is used to feed a Transformer architecture $\approx$ 1.5M of parameters.

ATL-PHYS-PUB-2023-021



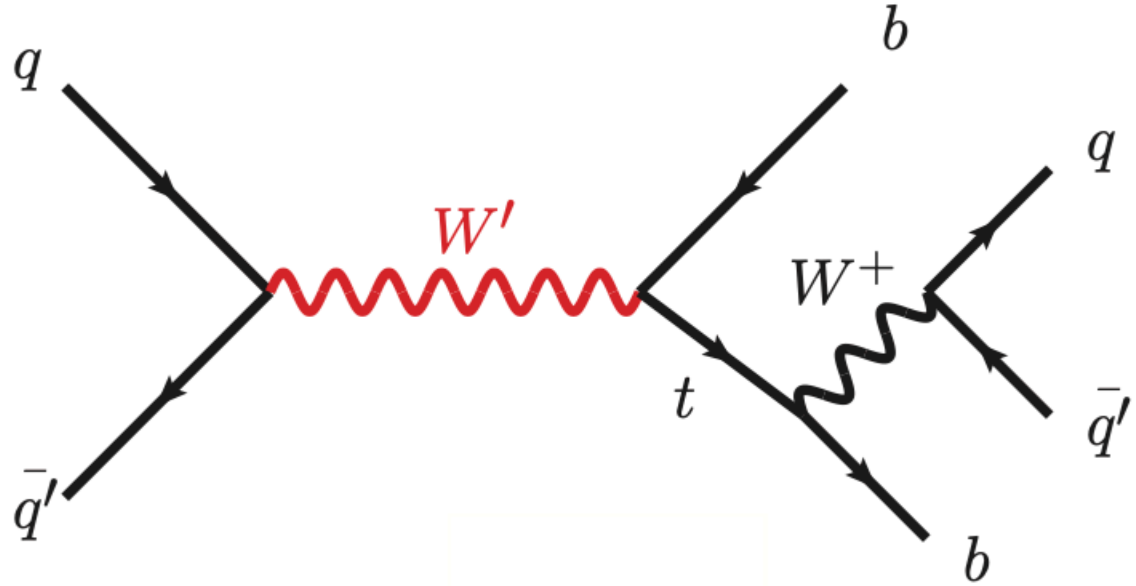


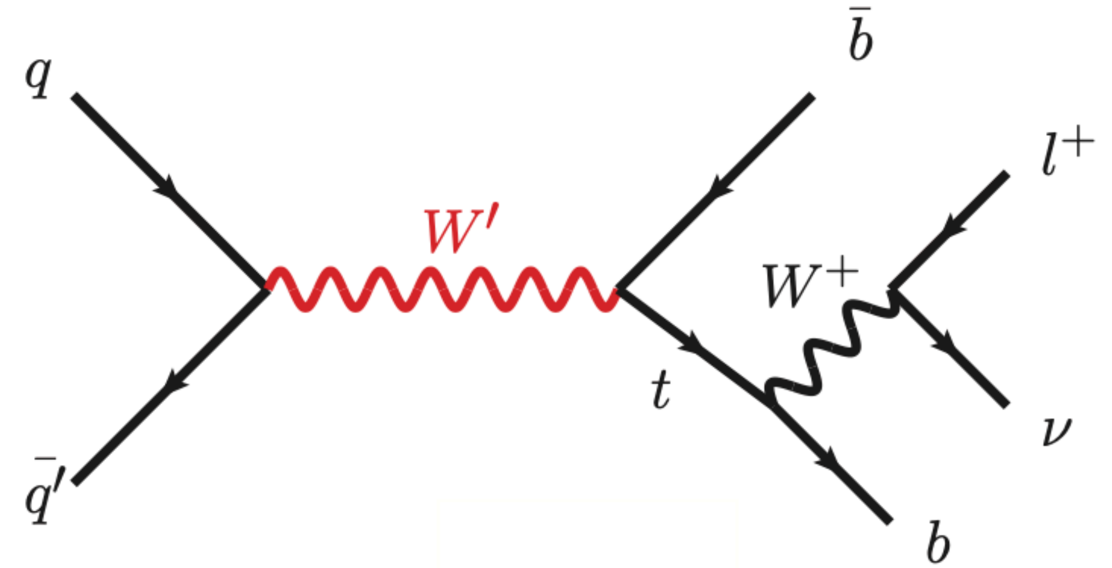
- A factor of 2.5 of improvement in multi jet rejection, having a 1.5 higher signal efficiency at $p_{\mathrm{T}} > 1$ TeV!

Physics analyses

$W' \to tb$ search (arXiv:2308.08521)

- Theories beyond the Standard Model (SM), involve enhanced symmetries that predict new gauge bosons, usually called W' or Z' bosons.
  - Different models/theories such us extra dimensions, strong dynamics predict new vector charged-current interactions, some with preferential couplings to quarks or third-generation particles.
    - Sequential Standard Model (SSM) to capture main phenomenology: $m_{W'}$, W_L/W_R, $\kappa = g'/g$
  - Focus on $W' \to tb$ decay channel.

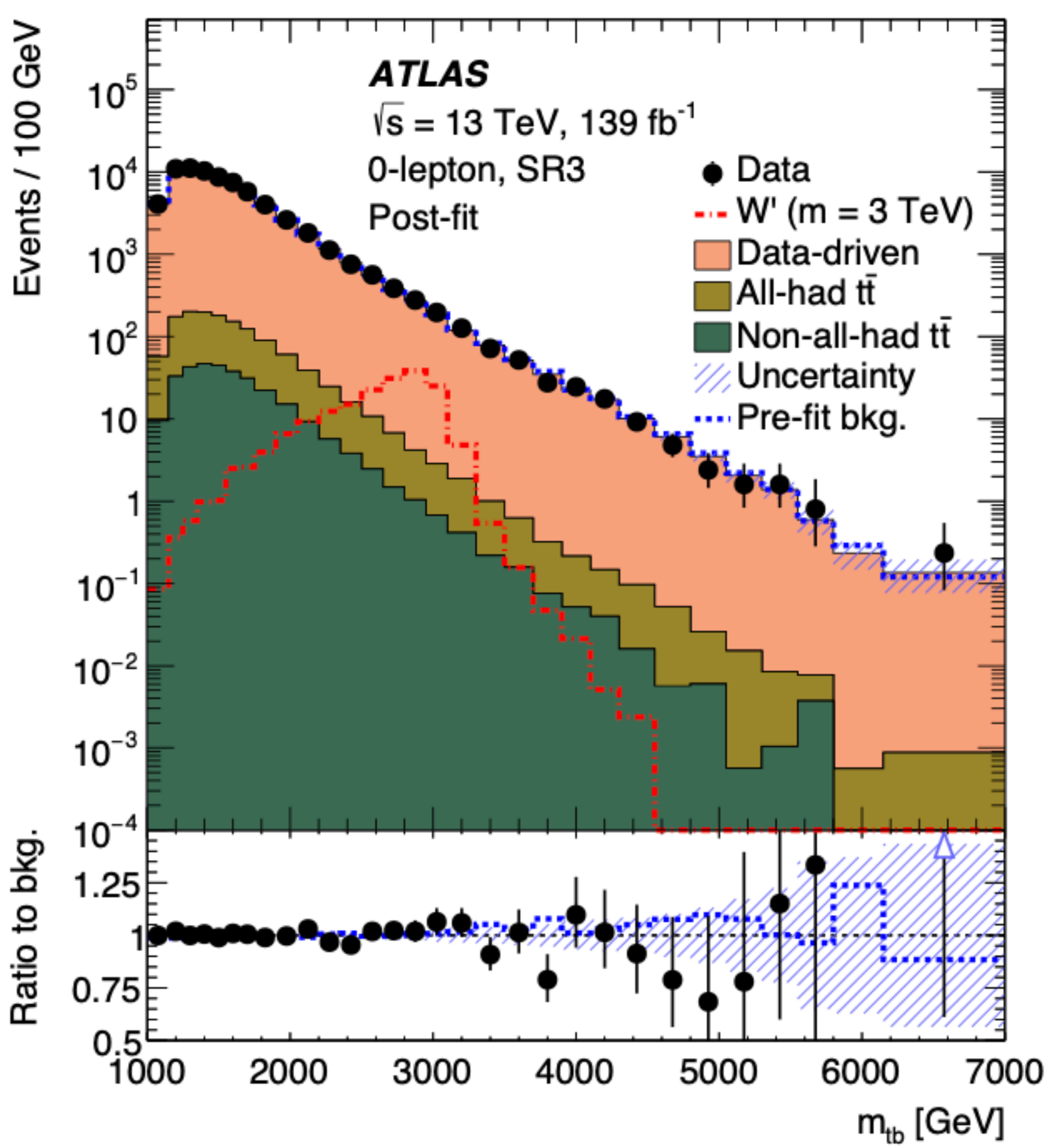


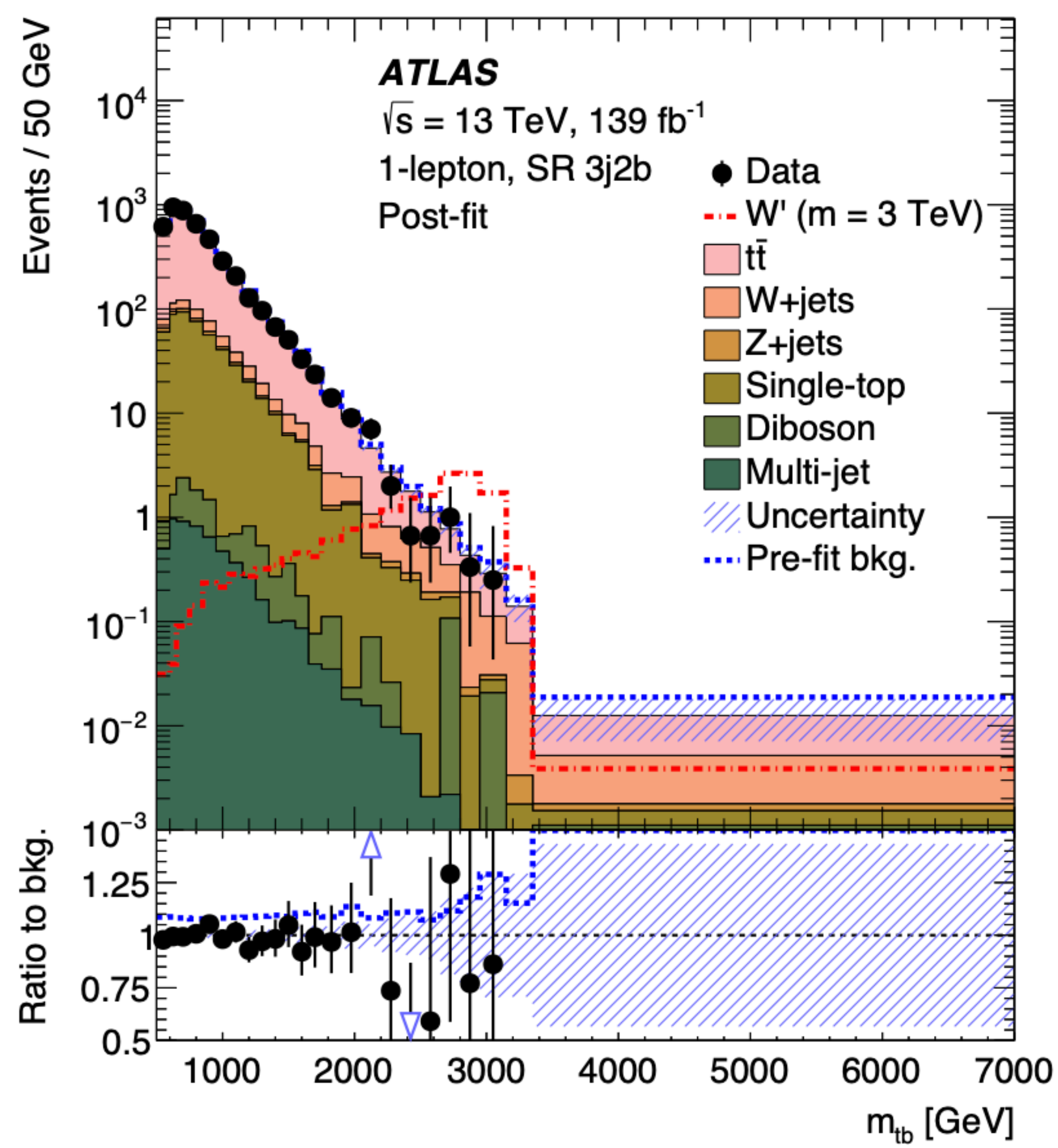


- Hadronic and leptonic top decay channels considered in this search.
  - For large $m_{W'}$, boosted tops will be produced: jet tagging techniques to identify hadronically decaying top → DNN top tagger!
- Different SRs are defined based on the number of final state b-jets (leptonic/hadronic channel) and DNN top tagger score (hadronic channel) to improve signal sensitivity.

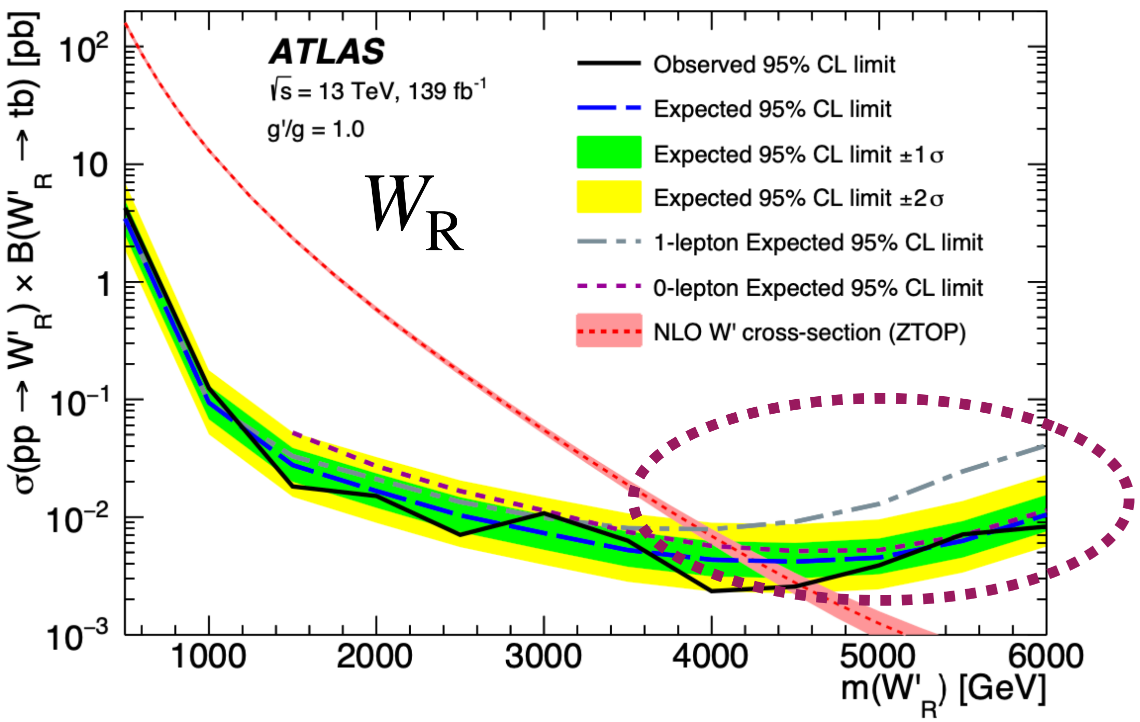
$W' \rightarrow tb$ search (arXiv:2308.08521)

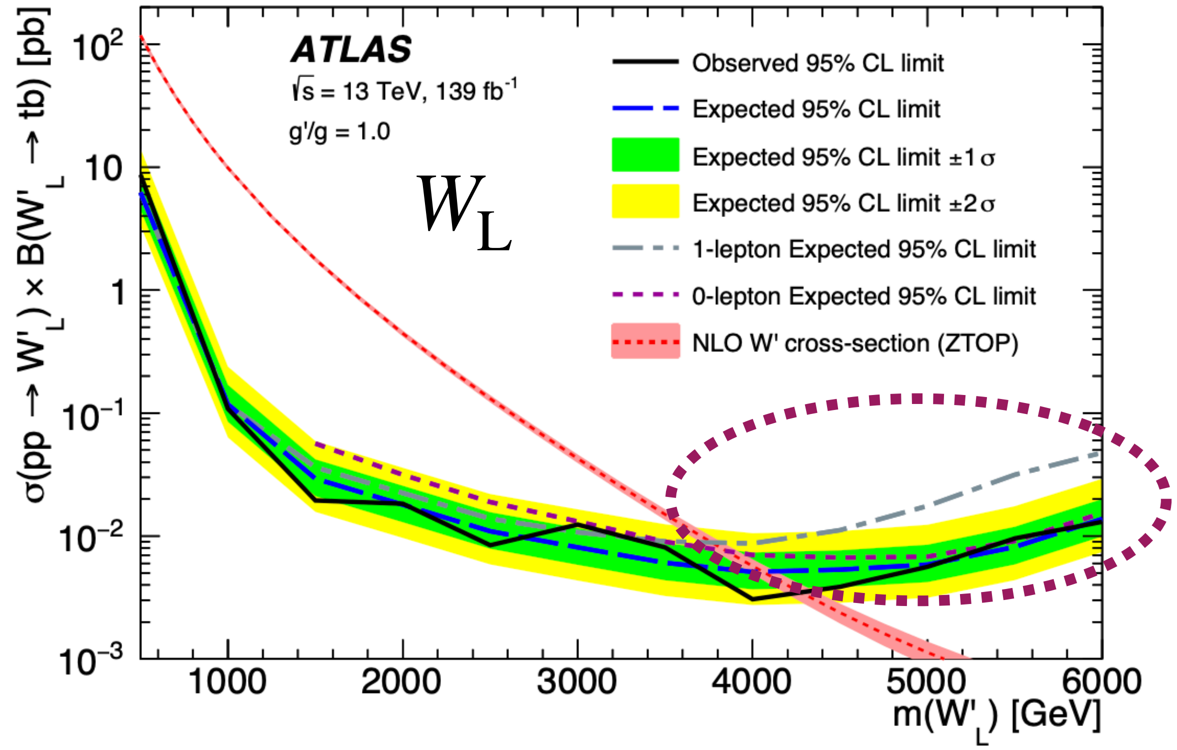
- Main backgrounds:
  - Leptonic channel: $t\bar{t}$, W+jets, Z+jets, single top
    - Dedicated control regions (CRs) to get insight on background norm./shapes.
  - Hadronic channel: mutlijet
    - Data-driven estimation based on dedicated CRs.
- Profiled binned likelihood fit to SR and CRs to test signal hypothesis.

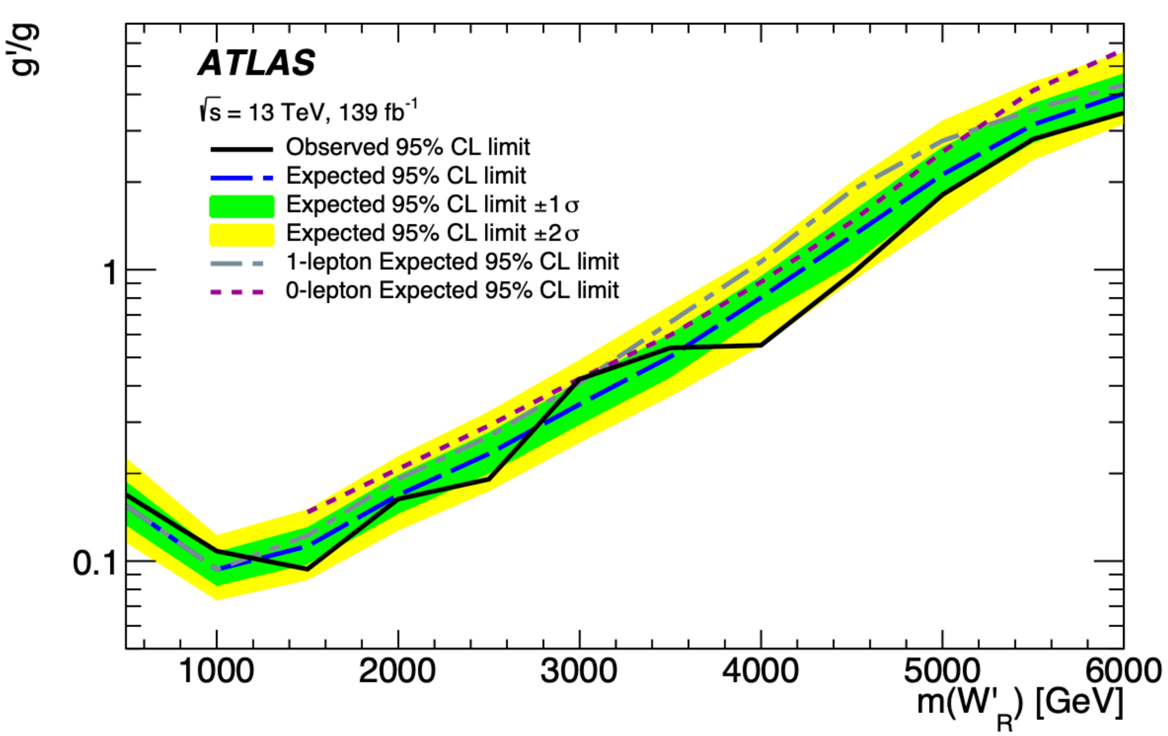


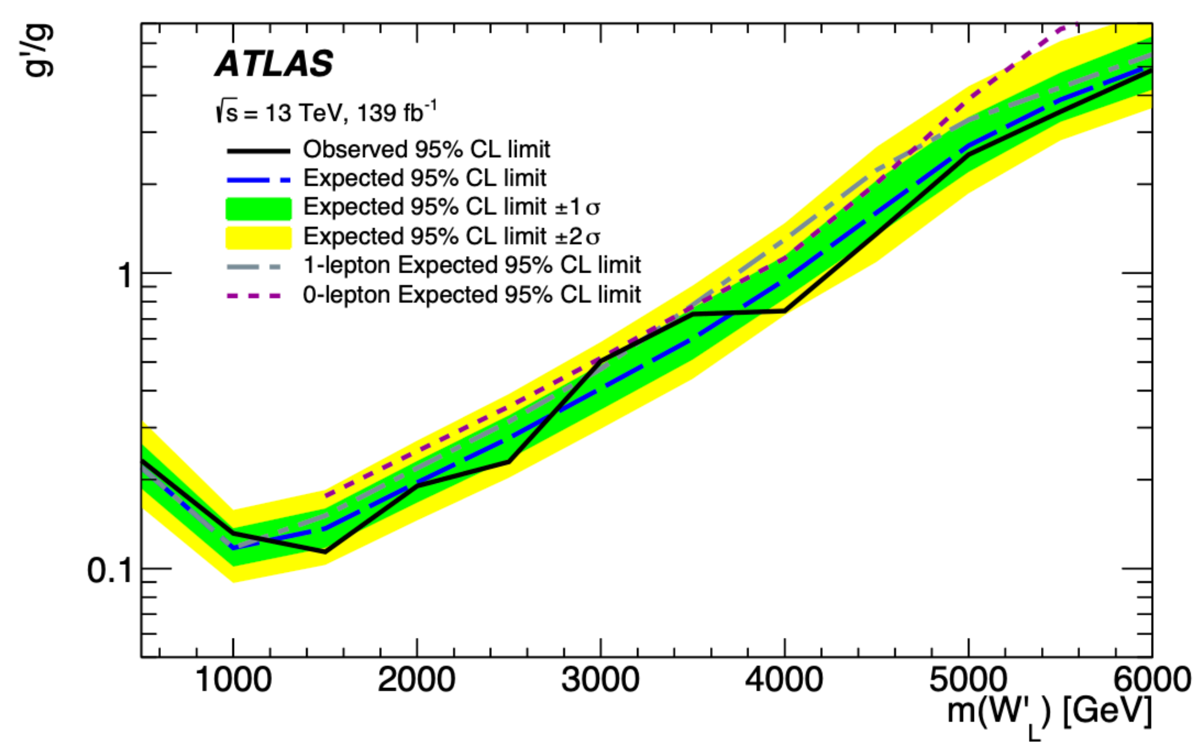


- 2D limits as functions of κ and $m_{W'_L}/m_{W'_R}$ are derived:
  - For $\kappa = 1.0$, right-handed (left-handed) W' with masses below 4.6 (4.1)TeV are excluded.





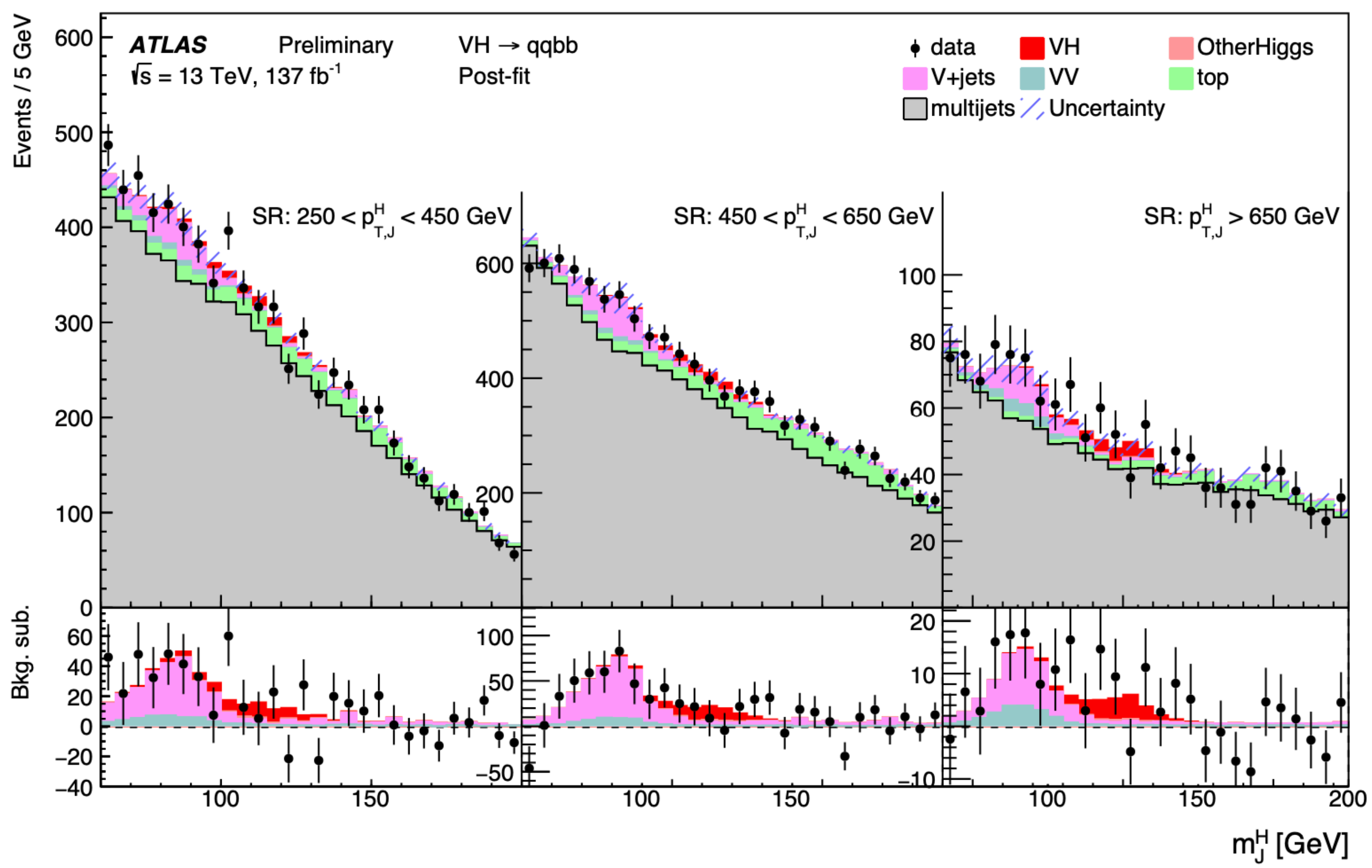




High p_T^H measurement in VH final state (ATLAS-CONF-2023-067)

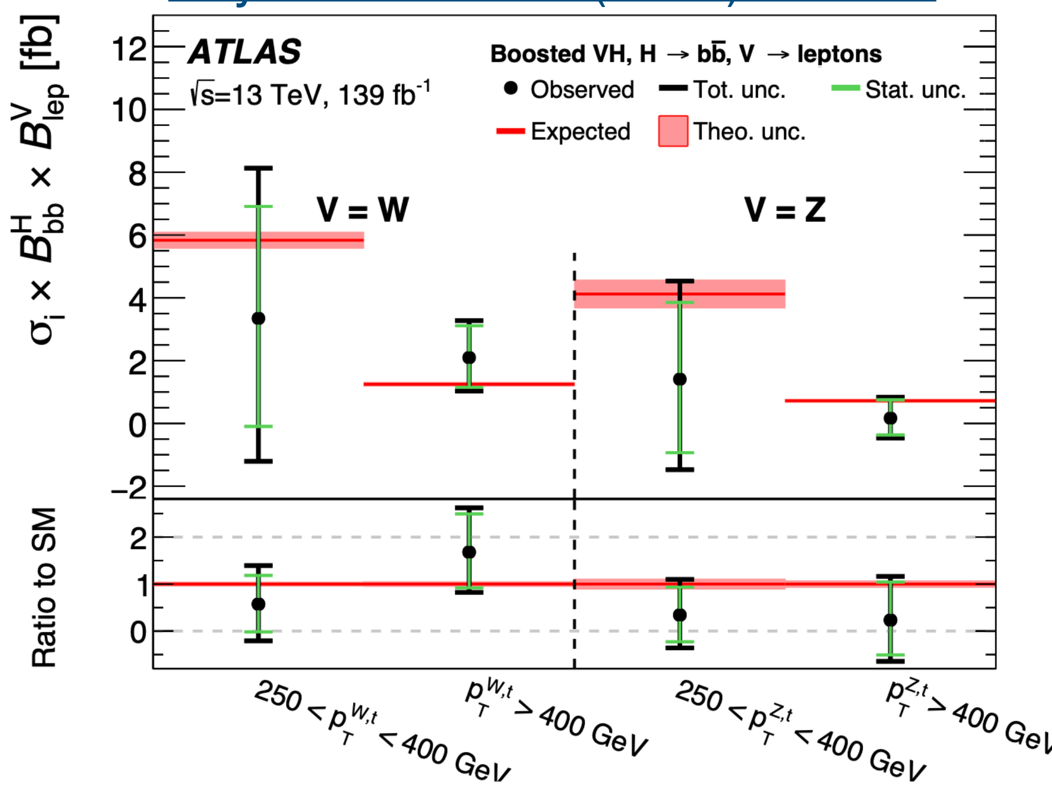
- The p_T^H distribution is measured in $pp \rightarrow V(q\bar{q})H(b\bar{b})$ processes.
  - Larger W/Z branching fraction in hadronic channels allows to extent the VH measurement beyond p_T> 400 GeV.
  - Main background coming form multi jet events estimated with a data-driven method.
  - W/Z and Xbb taggers applied to improve signal sensitivity.

- Signal strength estimated from fits to the mass of the Higgs candidate.

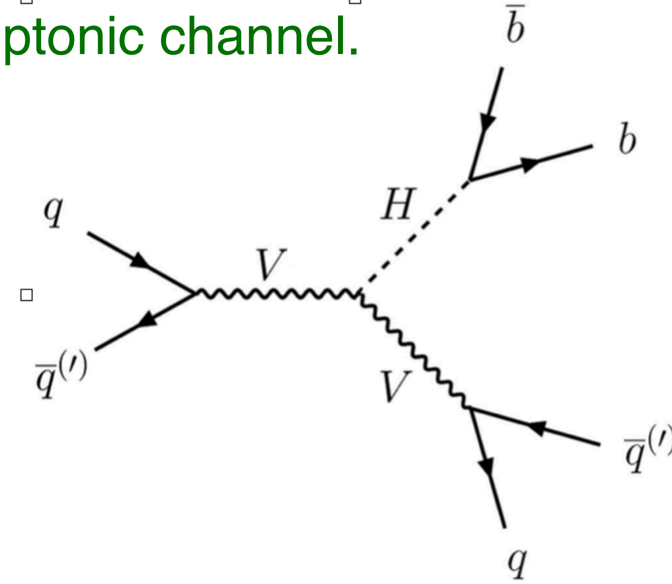


W/Z leptonic channel

Phys. Lett. B 816 (2021) 136204



- 2.1 (2.7)σ observed (expected) for VH signal in leptonic channel.



- 1.7 (1.2)σ observed (expected) for VH signal in hadronic channel.

Conclusions

- Jet tagging is a powerful tool which helps to improve signal sensitivity.
  - It allows to include hadronic decay channels of boosted resonances.
    - Larger branching fractions than leptonic channels.
  - In the case of boosted tops, typically better sensitivity at very large p_{T} compared to leptonic decay channel.
  - Fully reconstruct the event with Ws in the final state.
    - Not possible in $W \to l\nu_l$ decay channels.
  - Taggers need to be calibrated for an optimal use in physics analyses.

- On the experimental side, Large-R jet definition crucial to improve tagging performance.
  - Better grooming techniques, jet constituent definition …

- Machine learning usual technique these days to improve tagging performance.
  - Better architectures able to extract crucial information from quite low level jet inputs.
  - Challenge for the calibration: modelling dependence, pile-up stability …