Boosted W/Z tagging at ATLAS

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On behalf of the ATLAS experiment

BOOST 2016

18th – 22nd July, 2016

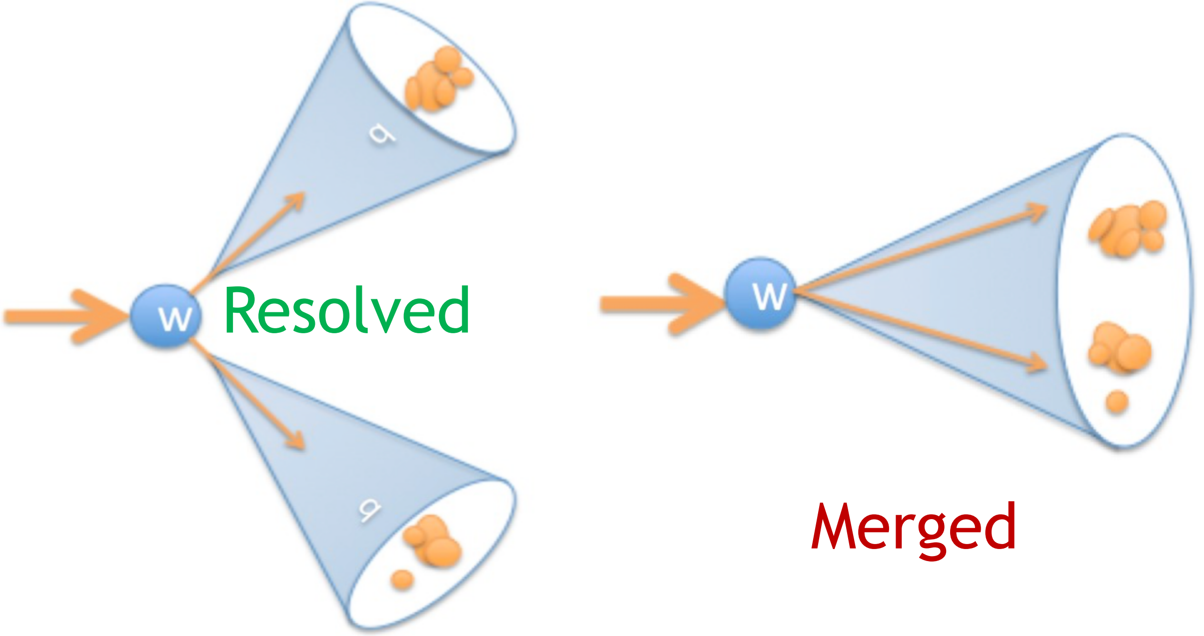
Why we need W/Z boson-jet tagging

- Hadron collider experiments deal with a large fraction of events from strongly produced jets - QCD multi-jet production
- XS of QCD multi-jet is much higher than W/Z signals → leptonic decays are studied to reduce QCD multi-jet backgrounds
- Bosons similar to W/Z are predicted in BSM theories which don't couple to leptons

When boson momentum >> mass, spatial proximity of decay products can help distinguish between QCD and W/Z-jets

- Many substructure algorithms have been studied in Run1

Tradeoff between using relatively pure leptonic decays of bosons and high-branching-ratio hadronic decays



Jet grooming techniques

- Remove soft component targeting Pileup (PU) and Underlying event (UE)
- Better signal-background separation
- Improves resolution of signal jet mass peak

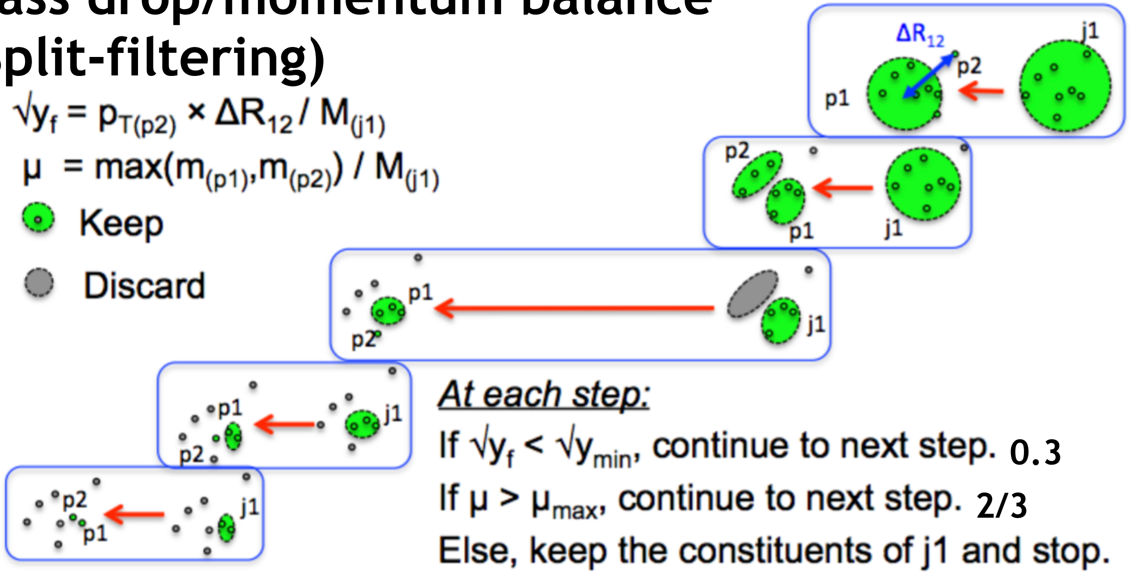
Mass drop/momentum balance (Split-filtering)

$\sqrt{y_f} = p_{T(p2)} \times \Delta R_{12} / M_{(j1)}$

$\mu = \max(m_{(p1)}, m_{(p2)}) / M_{(j1)}$

Keep

Discard



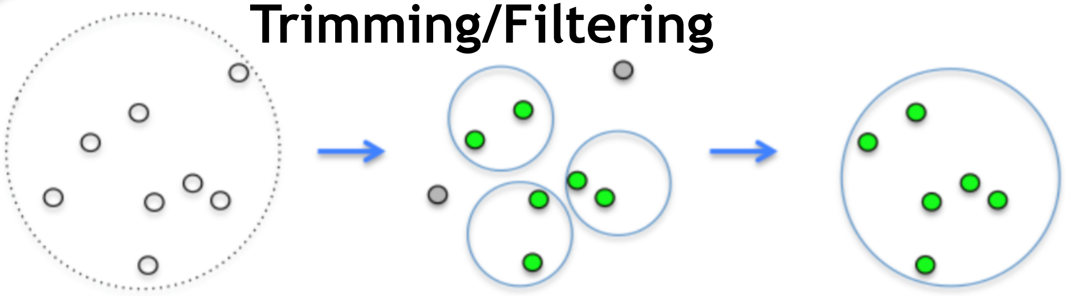
At each step:

If $\sqrt{y_f} < \sqrt{y_{min}}$, continue to next step. 0.3

If $\mu > \mu_{max}$, continue to next step. 2/3

Else, keep the constituents of j1 and stop.

Trimming/Filtering



Type 1 (Trimming) : If p_T (subjet i) / p_T (jet) < f_{cut} : discard subjet.

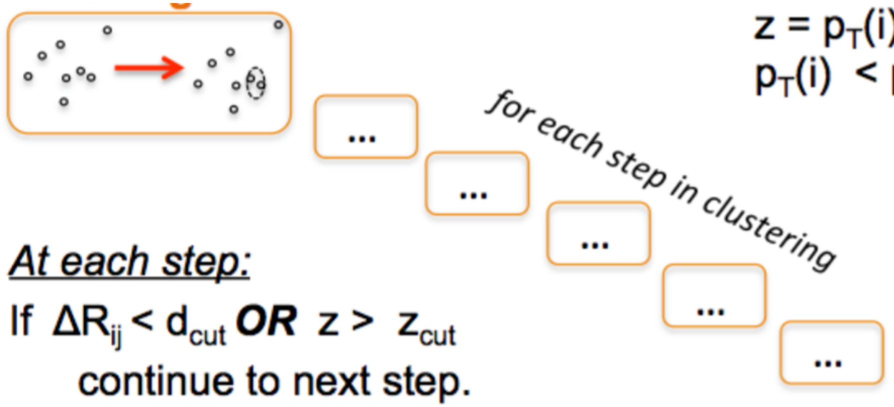
Type 2 : If $N_{subjets} \leq N_{min}$: discard jet.

Resulting jet is sum of subjets.

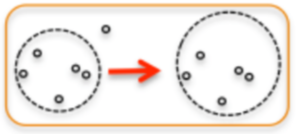
Pruning

$z = p_T(i) / p_T(i+j)$

$p_T(i) < p_T(j)$



Re-cluster via C/A or kT



At each step:

If $\Delta R_{ij} < d_{cut}$ ***OR*** $z > z_{cut}$

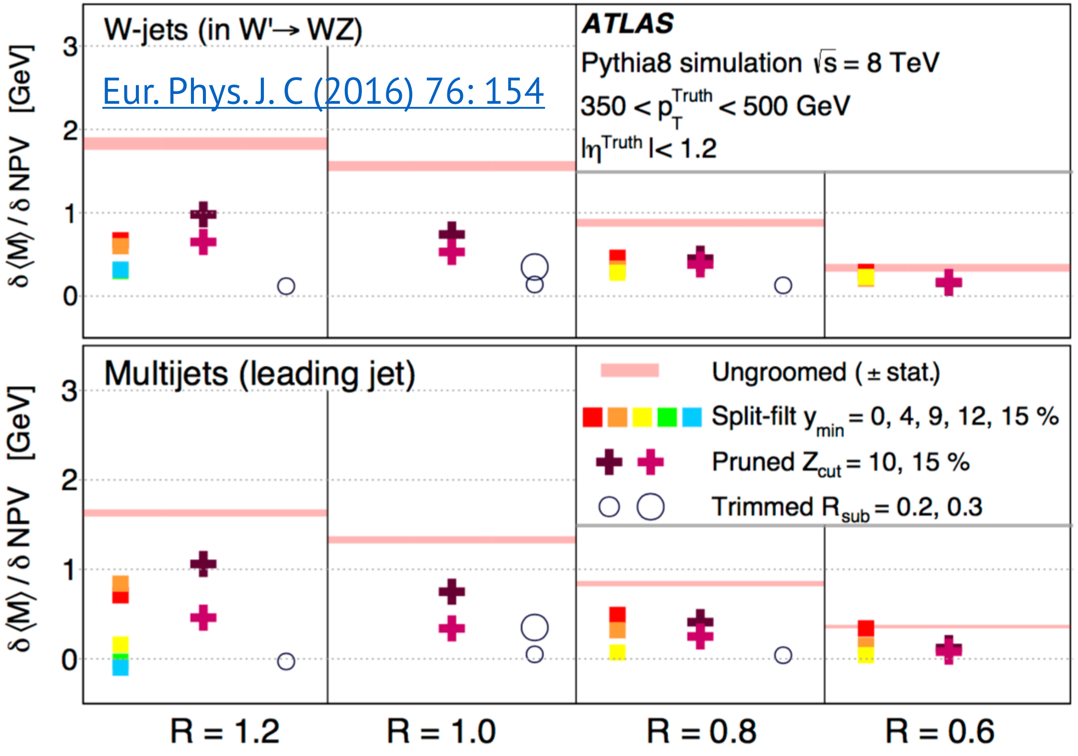
continue to next step.

Otherwise, discard object i.

Grooming techniques mentioned on previous slide have been studied in great detail in Run 1 and the best combinations have been studied in Run 2

- Trimming : various large R jet values, different R_{subjet} and f_{cut} values.
- Pruning : various large R jet values, different re-clustering algorithms, z_{cut} and R_{cut} values.
- Split-filtering: various large R jet values, R_{subjet} , mass drop fraction and y_{cut} values.

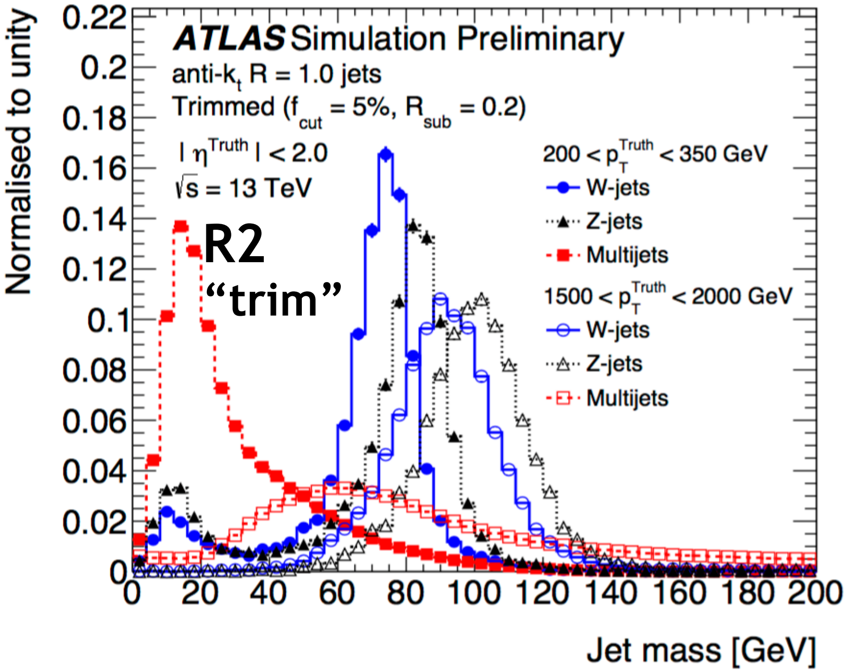
- **R2 ("trim"):** AntiKt, R=1.0 trimmed, R_{subjet} = 0.2, f_{cut} = 5%: **best BG rejection + PU stability**
- **P515 ("prun"):** C/A, R=1.0 pruned z_{cut} = 15%, R_{cut} = 1/2
  particularly good for W/Z-tagging at Pt ~500 GeV
- **Y15 ("SplitFilt15"):** C/A, R=1.2 split-filtered R_{subjet} = 0.3, y_{cut} >15%
- **Y4("SplitFilt4"):** C/A, R=1.2 split-filtered R_{subjet} = 0.3, y_{cut} **> 4%**

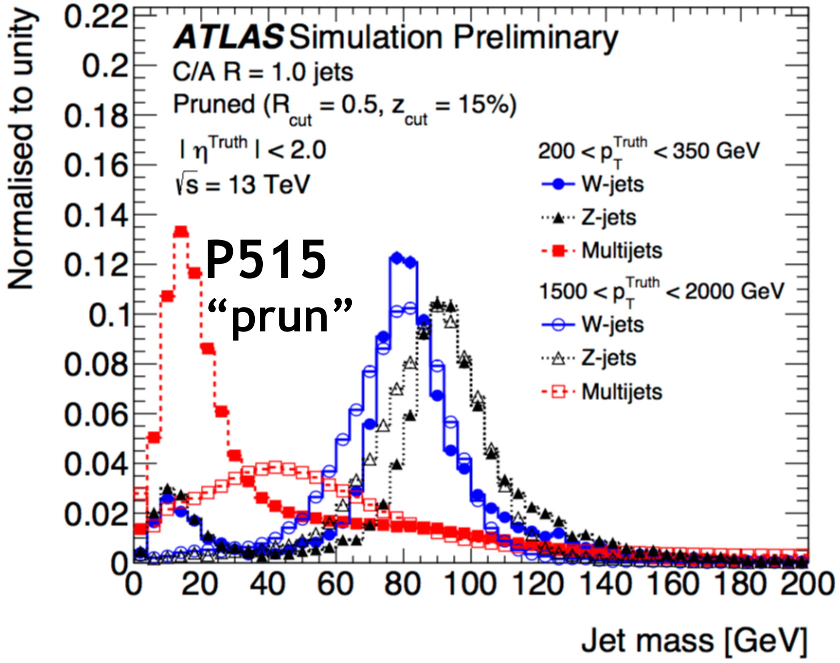


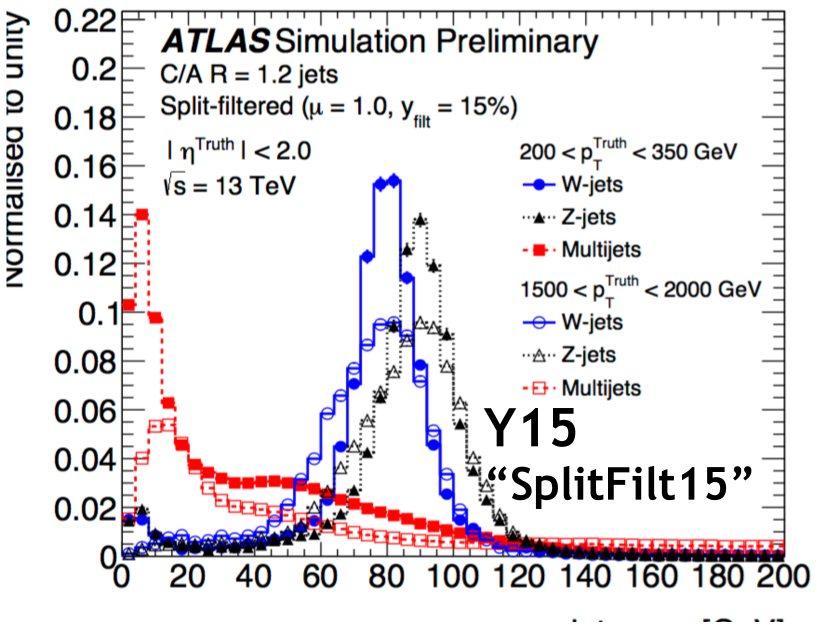
reduced pileup dependence after grooming: Each value of $\delta\langle M\rangle/\delta$NPV is the slope of a *straight line* fit of $\langle M\rangle$ versus NPV

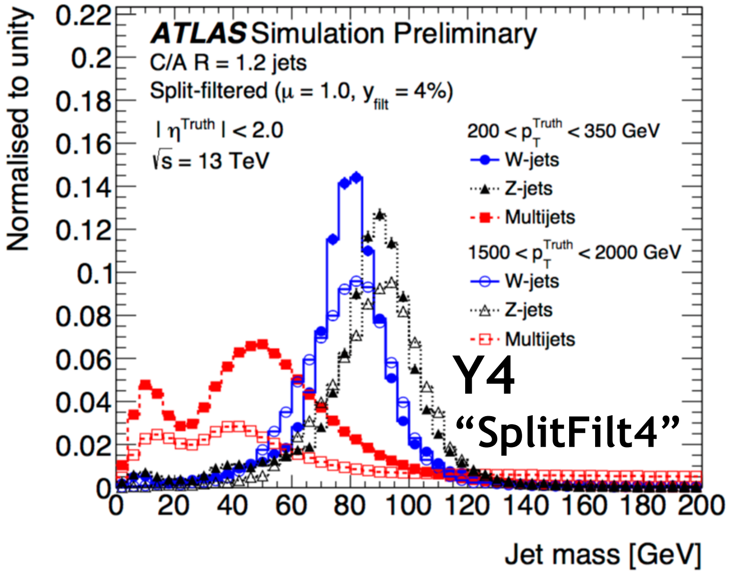
Jet mass after grooming

ATL-PHYS-PUB-2015-033





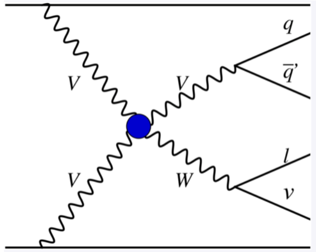




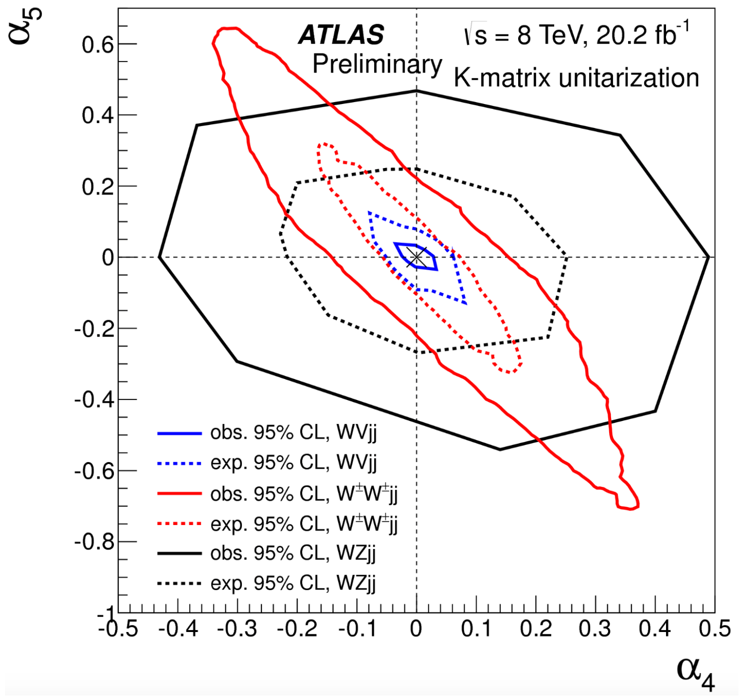
- No jet-level calibrations applied. Jet mass distributions for 200 < Pt < 350 GeV and 1500 < Pt <2000 GeV.
- R2 and p515: multi jet shape has strong dependence on Pt
- Y15 and Y4: more stable multijet shape across Pt bins
- W-jet and Z-jet mass shapes similar across Pt bins for Y4 and Y15

SM VBS search using groomed jets

STDM-2015-09

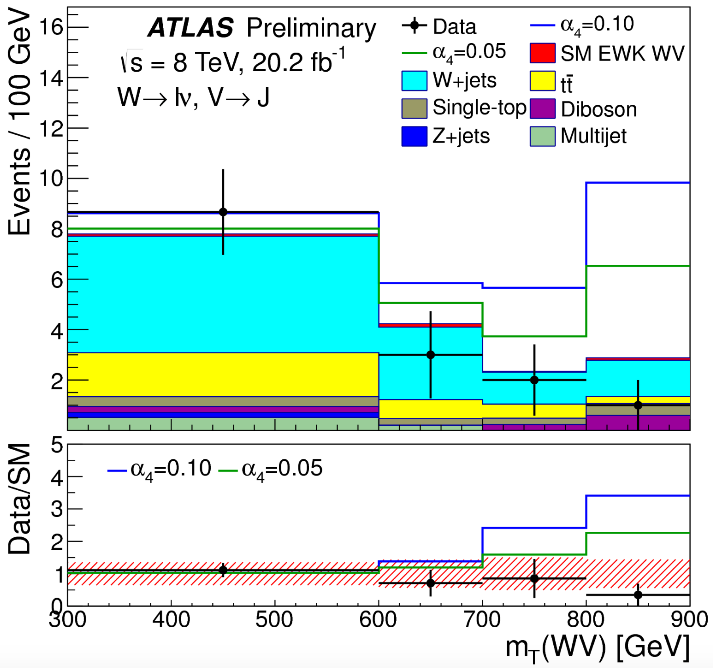


- Vector Boson scattering (VBS) with the W decaying hadronically and Z boson leptonically
  - Key probe of EW Symmetry Breaking
  - Sensitive to anomalous quartic gauge couplings: is the coupling as predicted by SM?
  - Previous searches for aQGCs in VBS have focused on leptonic decays—>smaller branching fraction
- Mass-drop filtered jets are used, for multiple large-R jets, the one with mass closest to the nominal W mass is used.



2D limits on aQGC parameters for current result (blue) and previous results (red).

- merged regime
  - aQGC limits are 40% better compared to only using resolved events.
  - most of the aQGC sensitivity comes from the highest-mT (W V) bins, where the merged category is powerful.
- More stringent limits obtained than the previous constraints on these parameters in searches for VBS in the W±W± and WZ leptonic decay channels

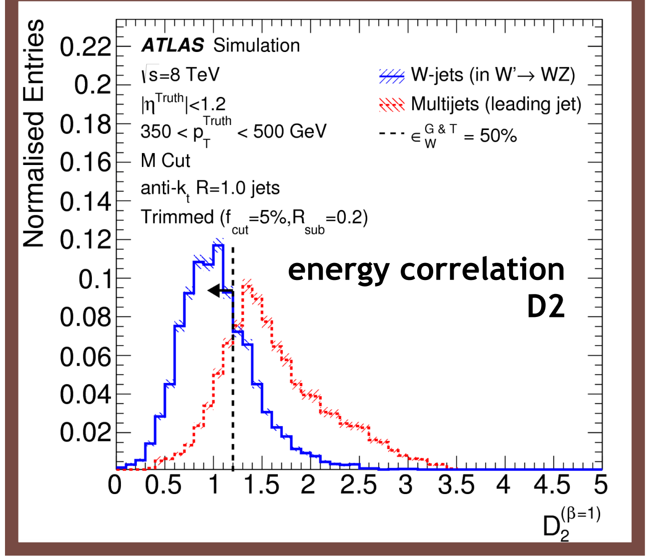


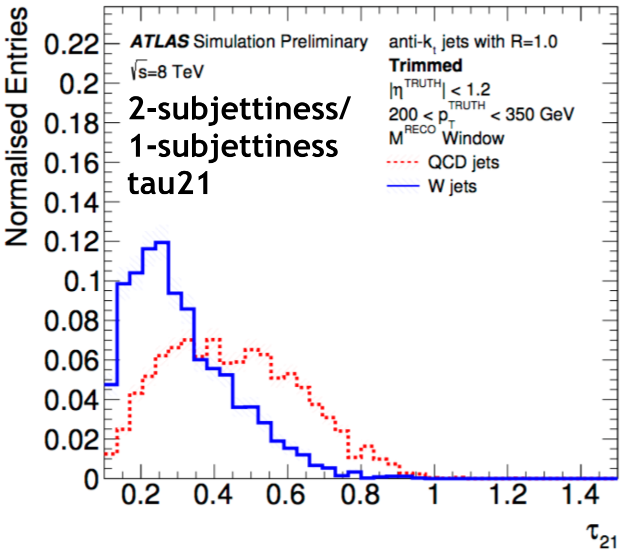
mT (W V) distribution used to extract aQGC limits: in merged regime

ATL-PHYS-PUB-2014-004

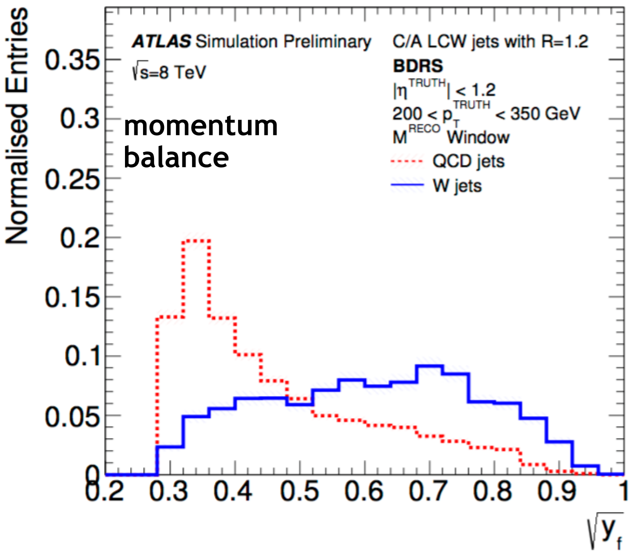
Eur. Phys. J. C (2016) 76: 154.

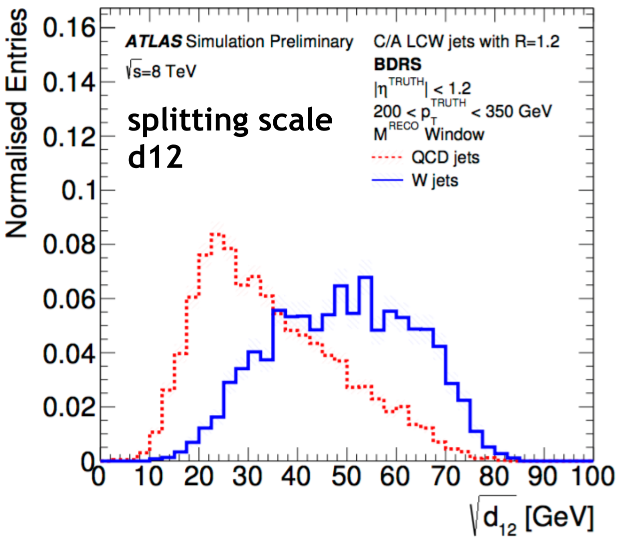
D2 validated with Run 2 data





signal and background discrimination using substructure variables

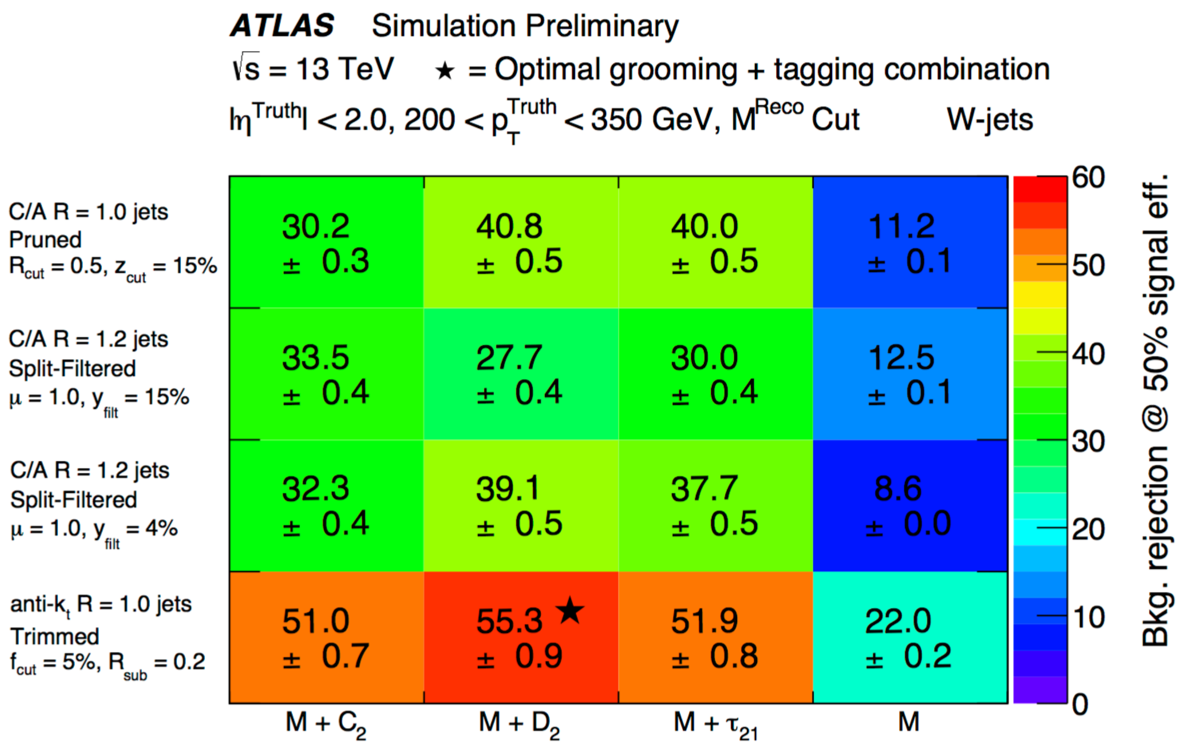




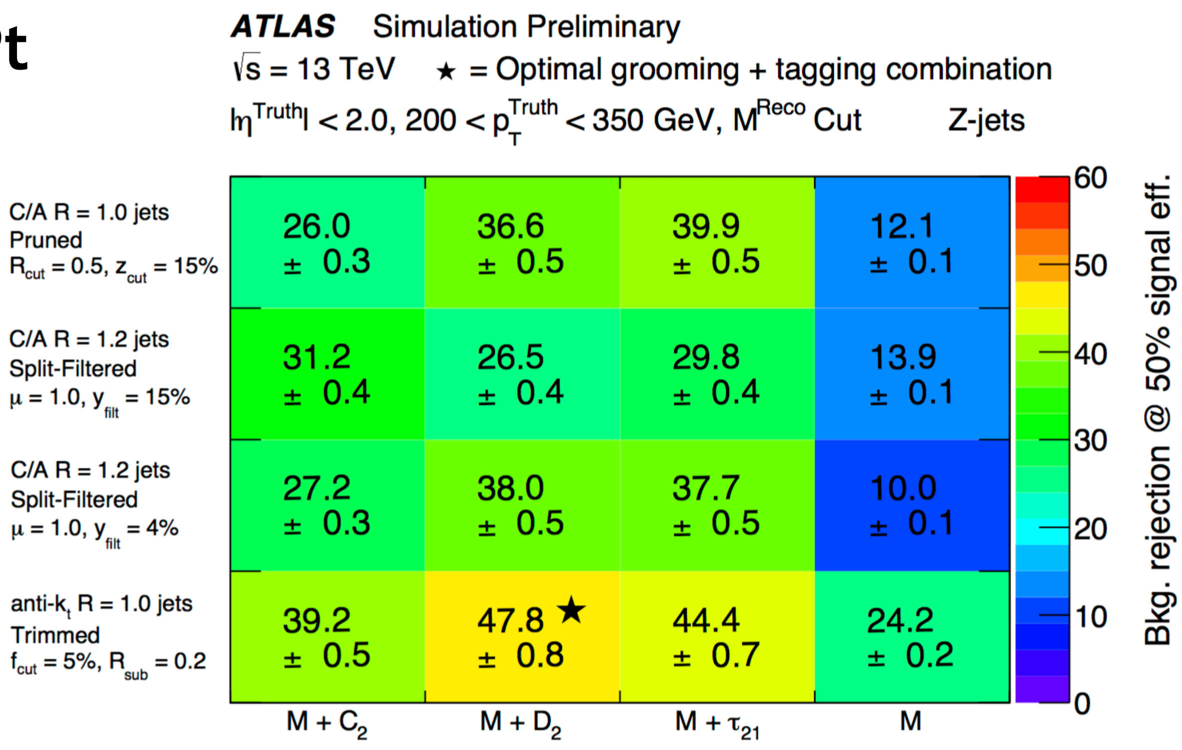
- **D2:** related to ratio of 3- and 2-point correlation functions. J. High Energ. Phys. (2014) 2014: 9.
- **N-subjettiness**: extent to which the substructure of a jet resembles N or fewer subjets. J. High Energ. Phys. (2011) 2011: 15.
- **Momentum balance**: ratio of splitting scale and jet mass of the final clustering step. Phys. Rev. Lett. 100, 242001
- **Mass-drop**: last step of recombination when two proto jets are combined into one. Fraction of mass carried by the most massive proto jet.
- **Splitting scale**: for a jet re-clustered with the Kt algorithm-Kt distance between two proto jets in the final clustering step. Phys. Rev. D 65, 096014
- **Jet width**: radial moment in eta, phi space weighted by Pt. Phys. Rev. D 86, 072006
- **Planar flow**: how uniformly spread out the jet energy is perpendicular to it's axis. Phys. Rev. D 79, 074017

mass window, plus tagging variables

Low Pt



W-jets



Z-jets

- M+C2,M+D2,M+t21: substructure + Mass, M: mass window (tighter) requirement only, 200 < Pt < 350 GeV, 50% signal eff.
- Mass only requirement yields higher background rejection for Z-jets than W-jets: Z boson mass is ~10 GeV higher than W boson so better separated than the multijet background.
- Tagger+mass combination yields better background rejection for W-jets than Z-jets – broader Z-jet mass distribution (slide 5) than differences in substructure variable distributions.

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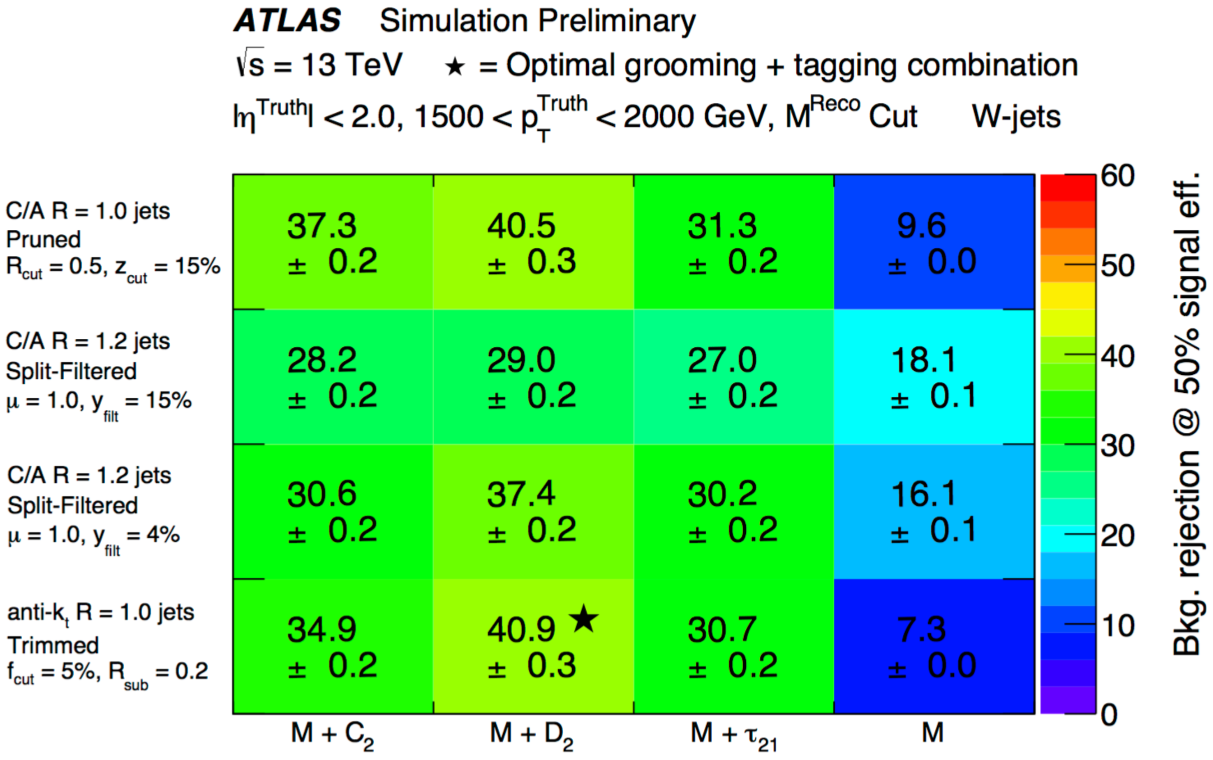
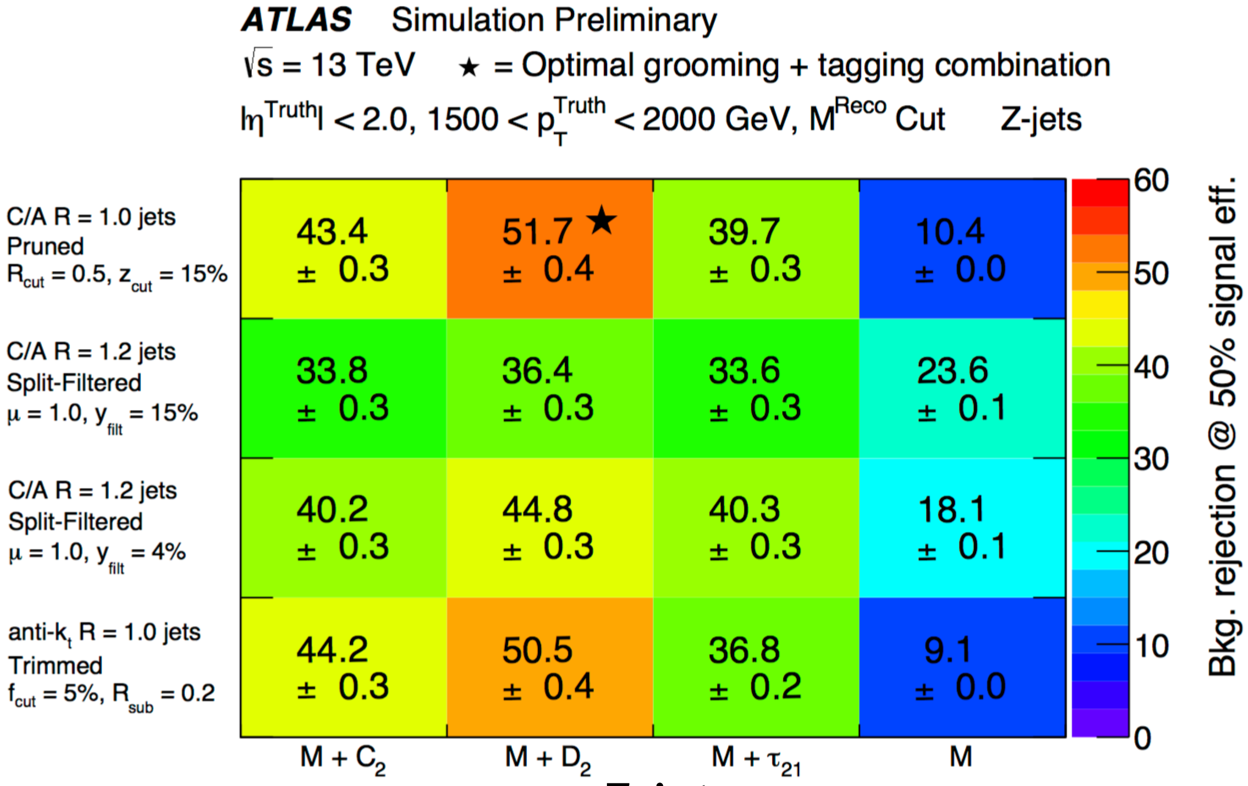
mass window, plus tagging variables

High Pt



W-jets



Z-jets

- M+C2,M+D2,M+t21: substructure + Mass, M: mass window (narrower) requirement only, 1.5 < Pt < 2TeV, 50% signal eff.
- At high pT, better background rejection for Z-jets than W-jets.

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Best performing: grooming+substructure

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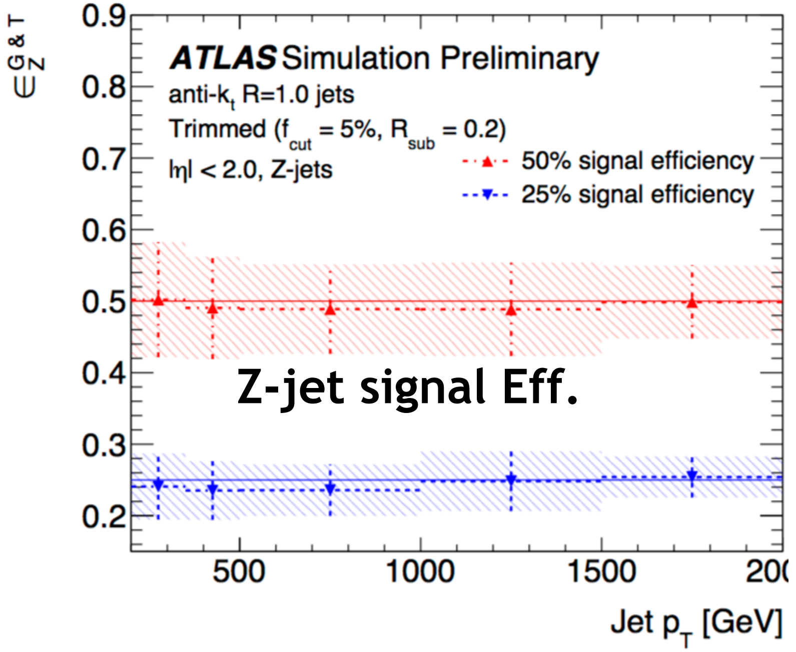
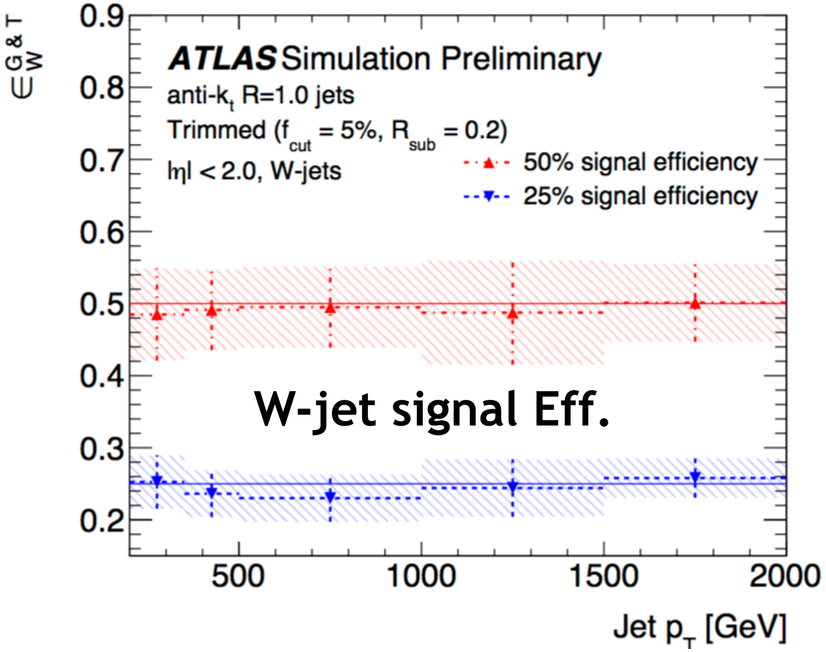
	Best G&T combinations in ranges of p_T^{Truth} [GeV]				
	250 – 350	350 – 500	500 – 1000	1000 – 1500	1500 – 2000
***W*-jets**					
Best 'Medium' tagger	R2 D_2 "trim"	P515 C_2 "prun"	P515 C_2 "prun"	P515 D_2 "prun"	R2 D_2 "trim"
$1/\epsilon_{QCD}^{G\&T}$	55.3 ± 0.9	71.5 ± 0.8	70.0 ± 0.7	55.2 ± 0.5	40.9 ± 0.3
Best 'Tight' tagger	R2 D_2	P515 C_2	P515 D_2	R2 D_2	R2 D_2
$1/\epsilon_{QCD}^{G\&T}$	215 ± 7	271 ± 5	274 ± 6	254 ± 4	188 ± 3
***Z*-jets**					
Best 'Medium' tagger	R2 D_2 "trim"	P515 C_2 "prun"	P515 C_2 "prun"	P515 D_2 "prun"	P515 C_2 "prun"
$1/\epsilon_{QCD}^{G\&T}$	47.8 ± 0.8	65.4 ± 0.8	67.1 ± 0.7	65.3 ± 0.6	51.7 ± 0.4
Best 'Tight' tagger	R2 D_2	P515 C_2	P515 D_2	R2 D_2	R2 D_2
$1/\epsilon_{QCD}^{G\&T}$	179 ± 5	255 ± 5	259 ± 6	270 ± 5	232 ± 4

- P515 and R2 with C2 and D2 perform particularly well
- Signal Efficiency:
  - Medium: 50%
  - Tight: 25%
- G&T: grooming and tagging
- Grooming algorithms
  - R2
  - P515
- Tagging variables
  - D2
  - C2
- $1/\epsilon_{QCD}$: background rejection for QCD multijets
- Only stat uncertainties shown

Systematic uncertainties on Signal efficiency and Background rejection

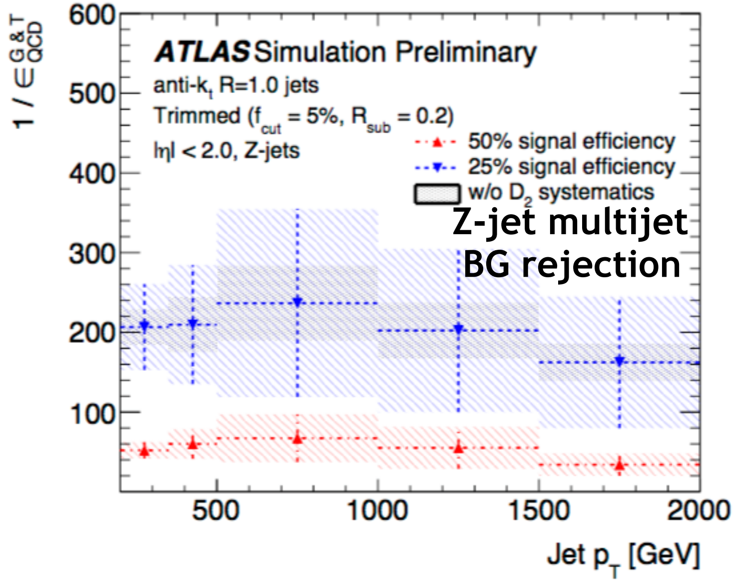


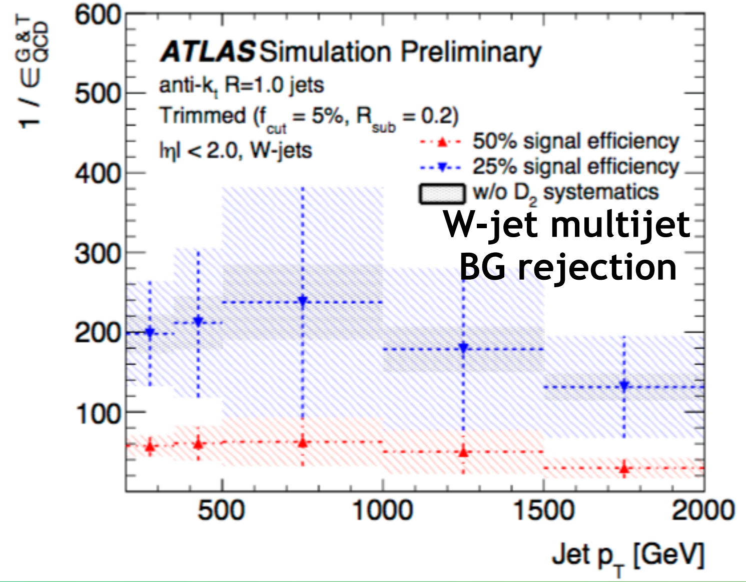


Signal efficiency and background rejection in MC only for two tagger working points:

- medium (50% signal efficiency)
- Tight (25% signal efficiency)

$$\varepsilon_{MC} = \frac{N^{\text{tagged}}_{\text{Boosted}-W}}{N^{\text{pre-tagged}}_{\text{Boosted}-W}}$$





D2 tagger related uncertainties dominate at high Pt.

ATL-PHYS-PUB-2015-033

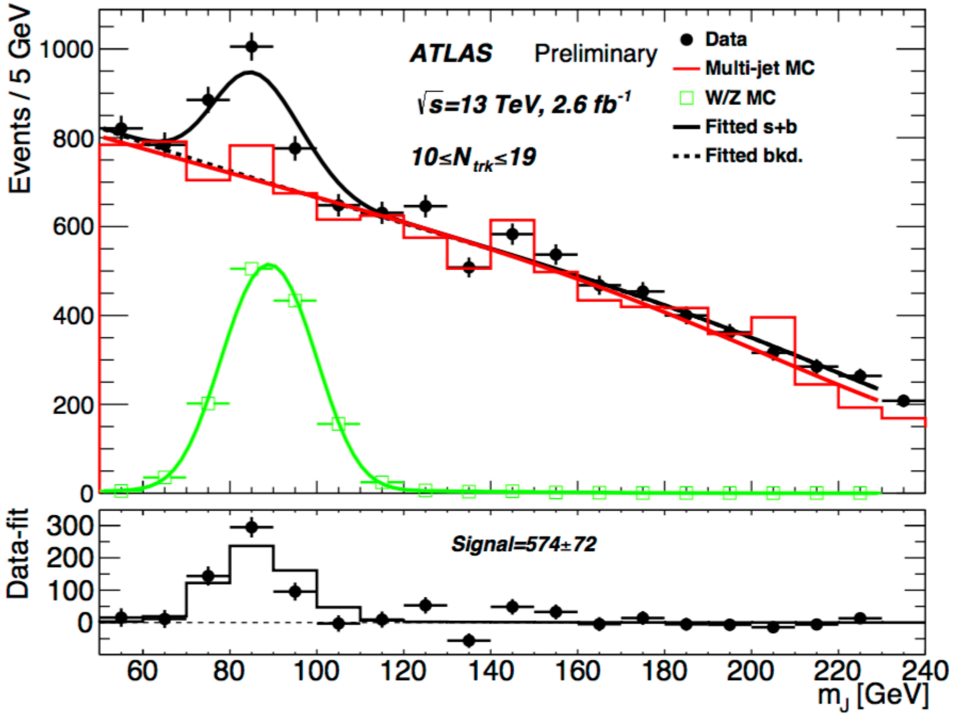
Boson tagging and track multiplicity

- Gluon-induced jets contain more charged hadrons than quark-induced jets. The number of tracks associated with the boson jet versus the background QCD jet can be used to provide further discrimination than the standard tagging requirements —> BG has a significant gluon contribution

- This is applied by cutting on the number of associated tracks with a jet : tracks are matched to the jet via ghost association.
- Requirement that Ntrk < 30 after grooming and substructure variable related cuts.

Ghost association: Add multiple constituents for jet finding with negligible momentum and with same direction as track, for each track.

optimized medium (50% signal eff.) D2 selection for the R2 configuration is used.

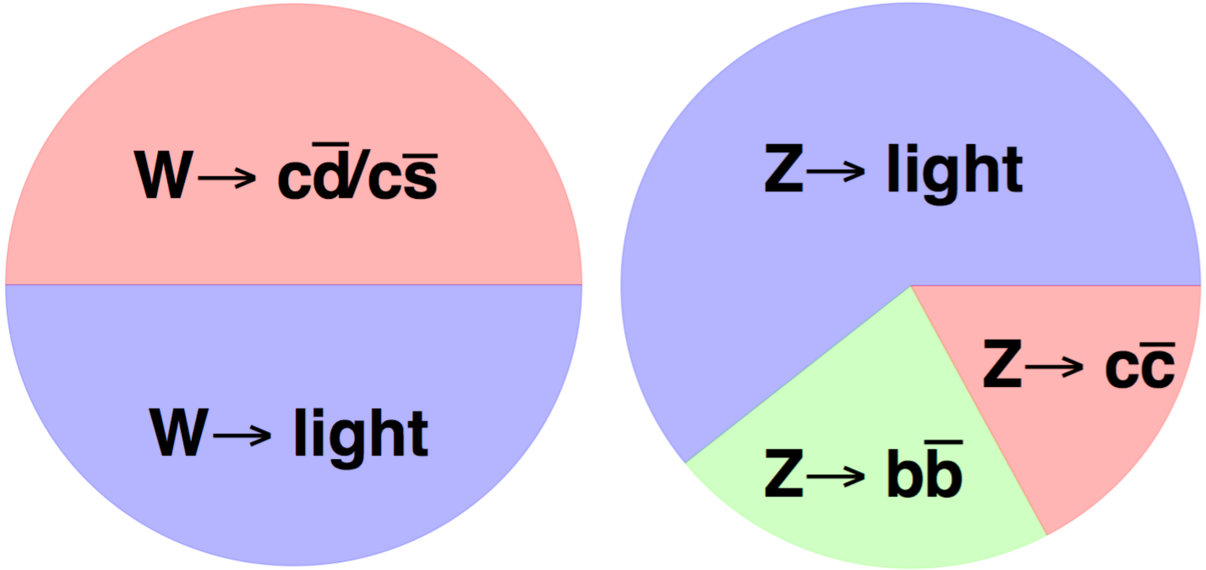


Validation of ntrack selection in data in 10 < Ntrk < 19 bin

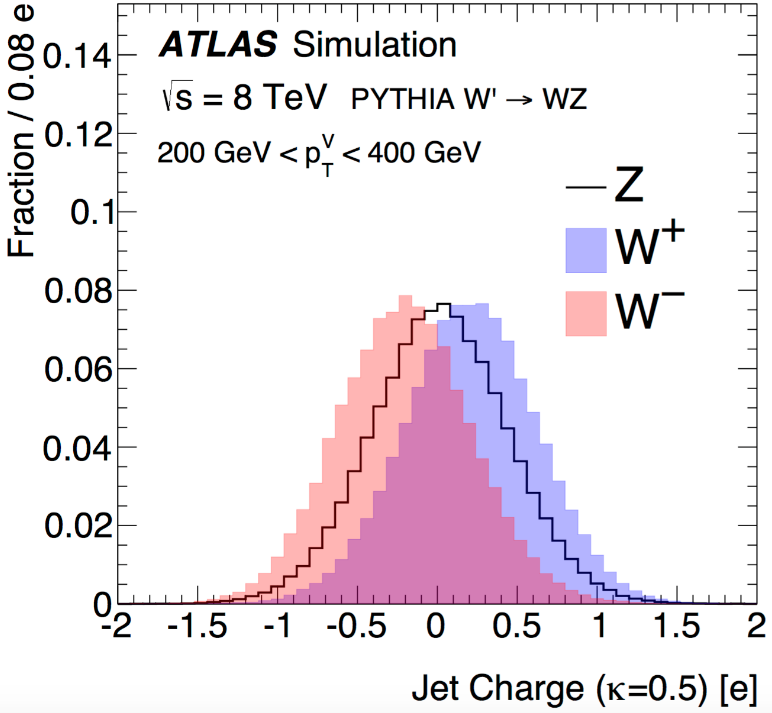
expected sensitivity of the analysis is improved by about 30% by using the additional Ntrk selection.

Distinguishing W-jet and Z-jet

- Differences in production XS and subtle differences in differential decay.
- Differentiating features: mass, charge and branching ratios.
- Variables considered for likelihood tagger for W-jet and Z-jet separation
  - Jet mass – sensitive to boson mass
  - Jet charge – sensitive to boson charge
  - B-tagging discriminant – sensitive to heavy flavor decay branching fractions of the bosons

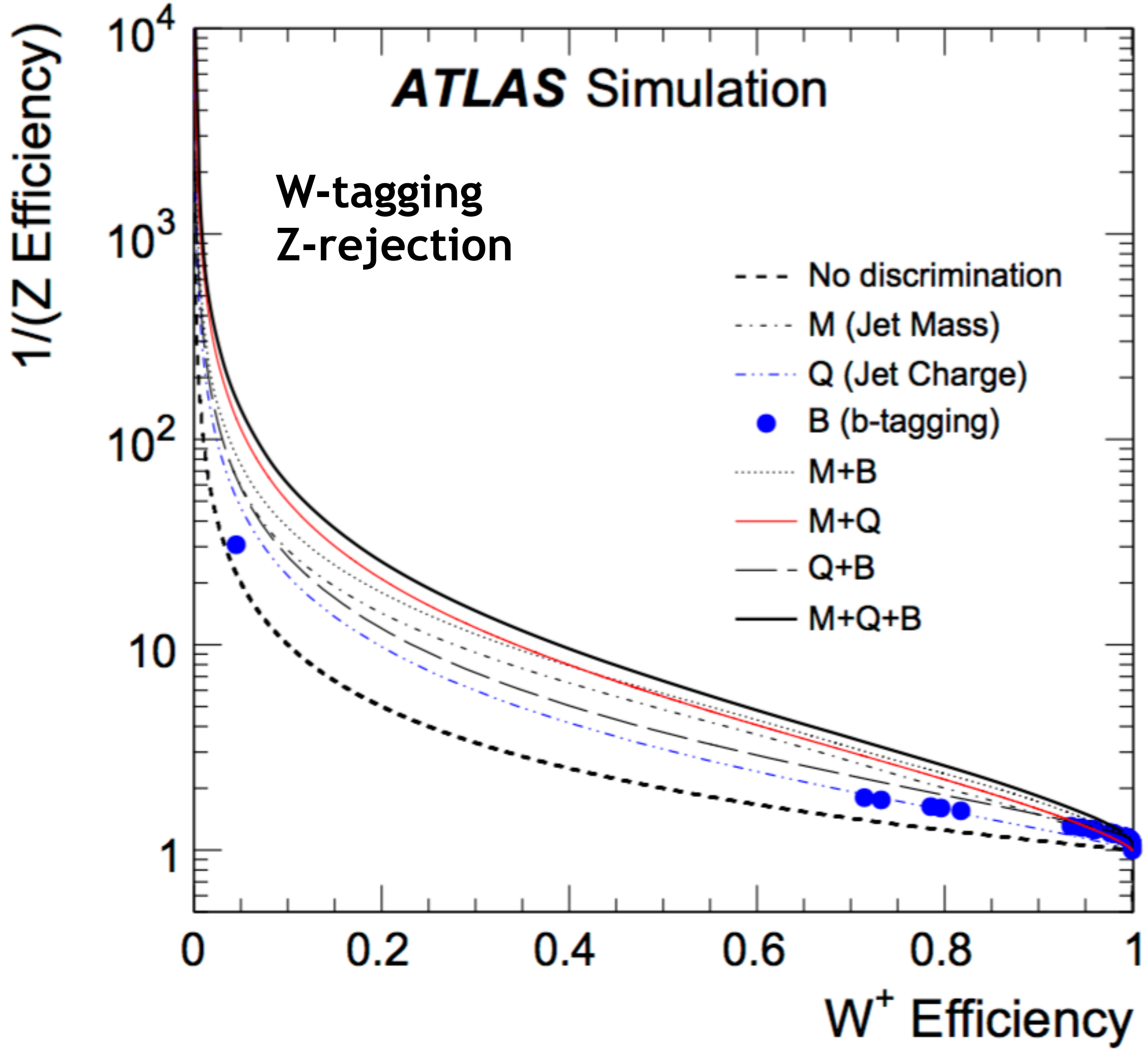


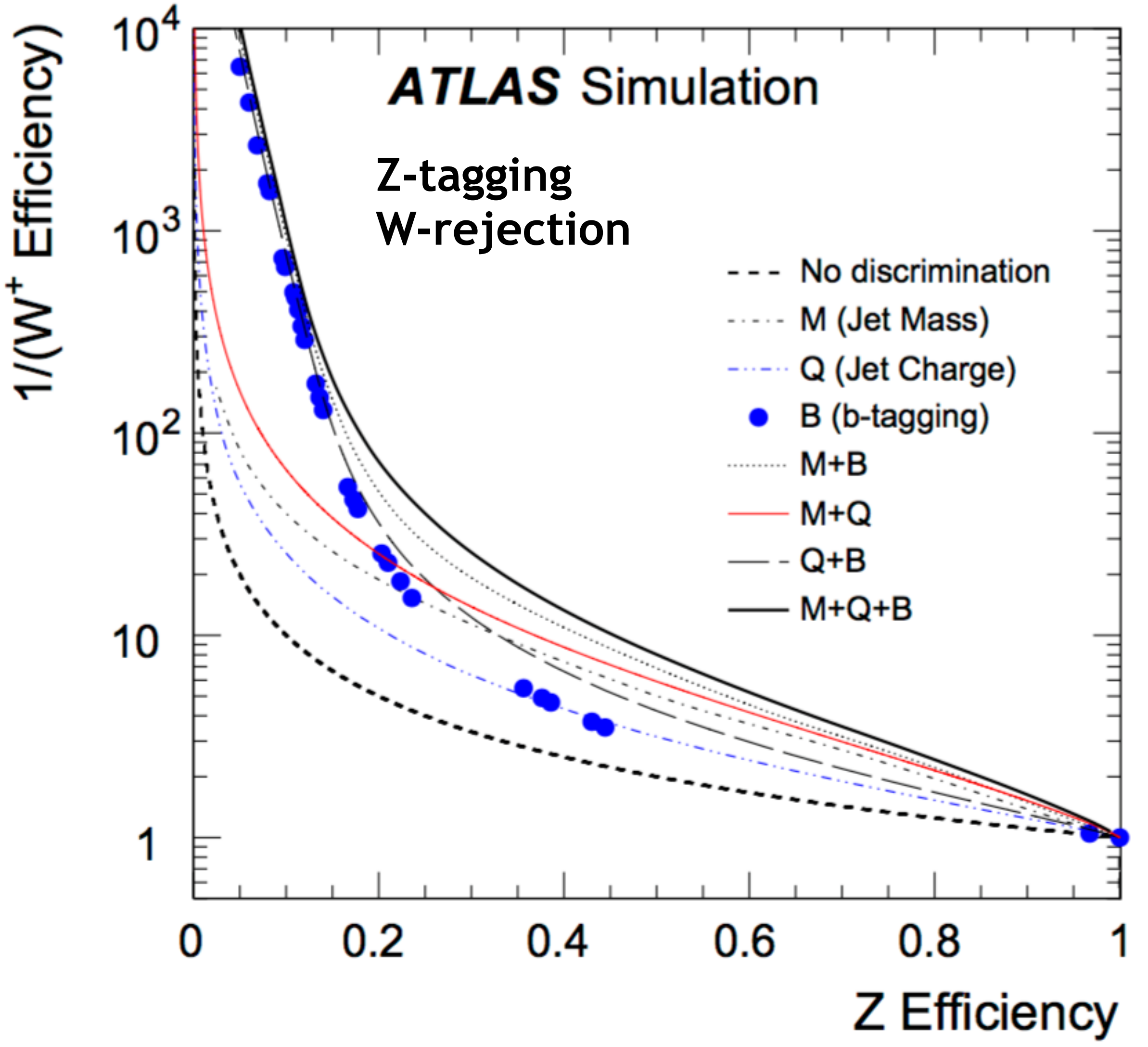
hadronic branching fractions of the *W*+ boson, and *Z* boson



W/Z efficiency and Z/W rejection

Eur. Phys. J. C (2016) 76: 238.

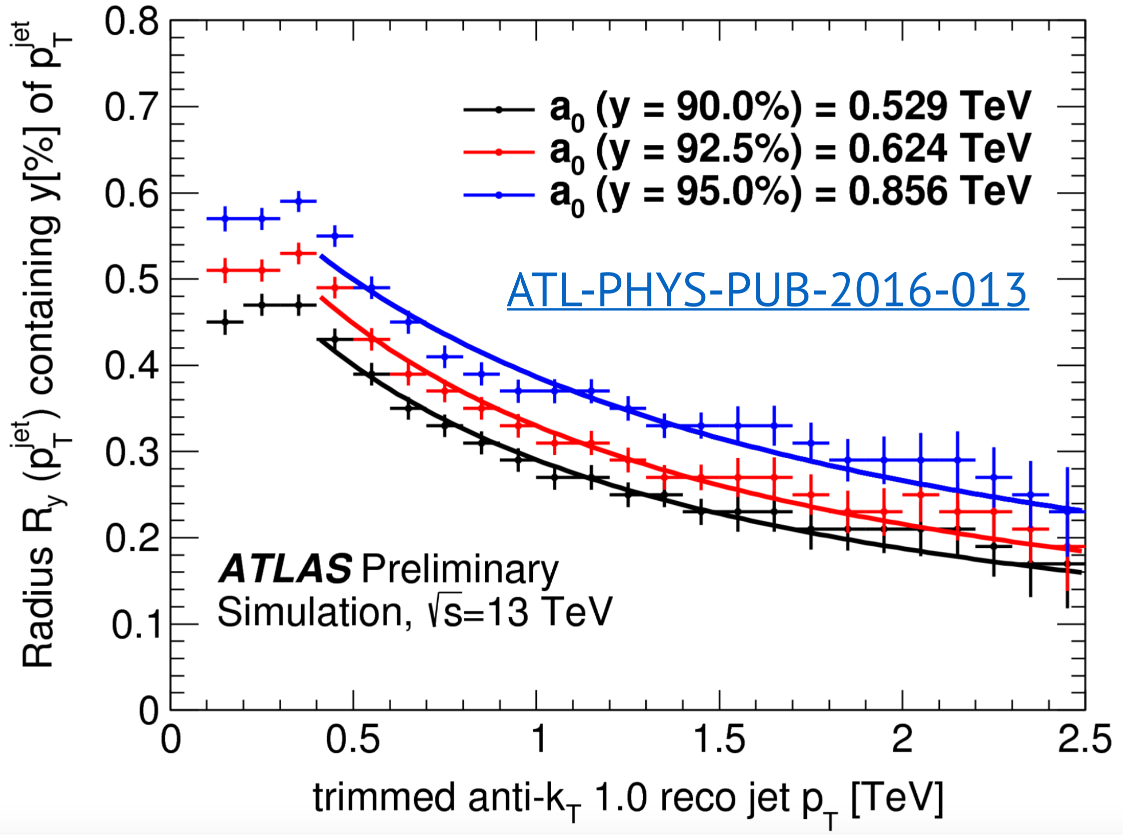


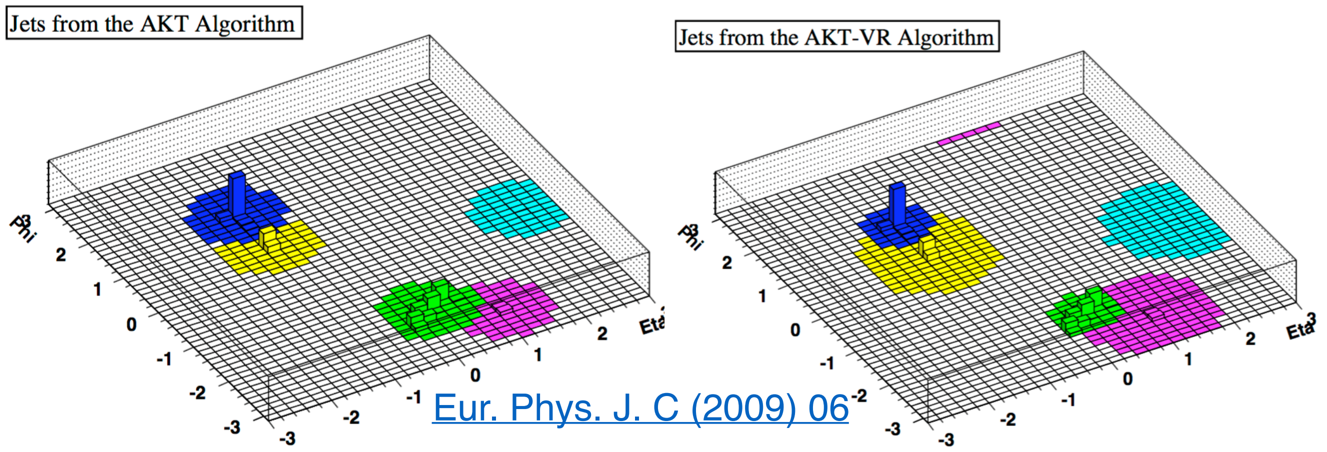


At low Z-tagging efficiencies, large W rejection due to Z→bb tagging

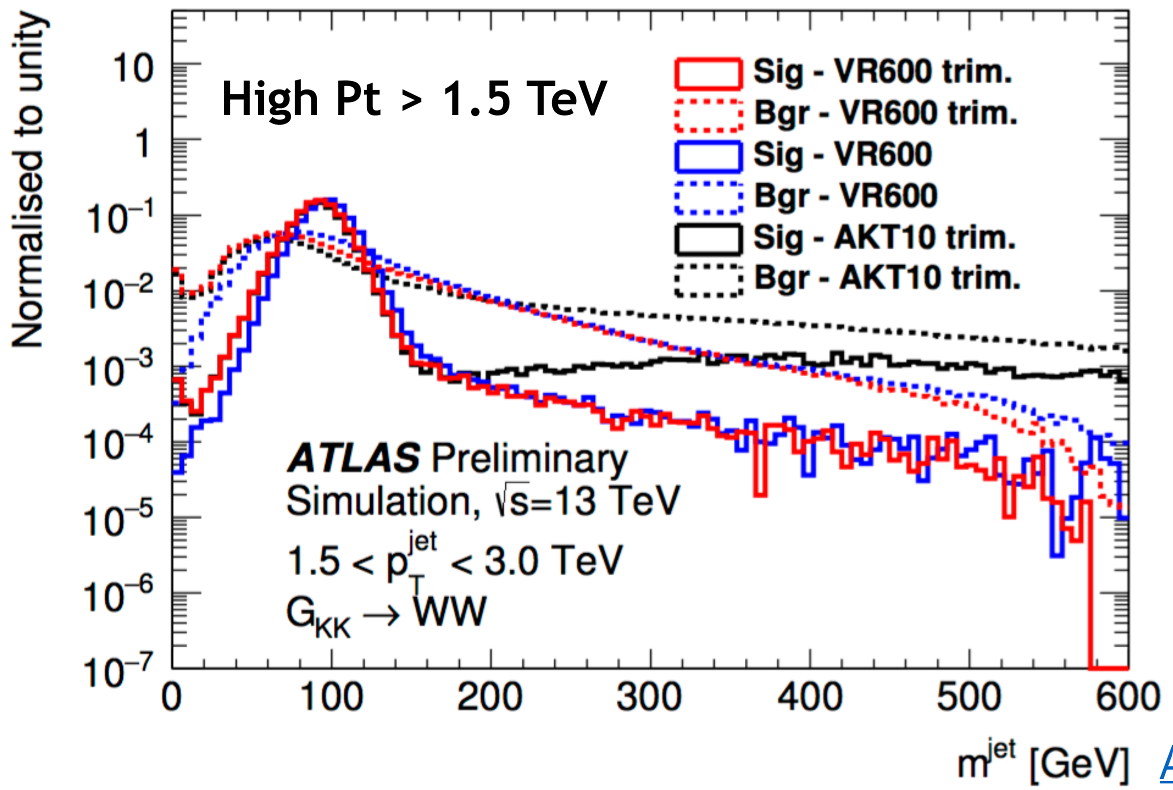
Tagging using variable-R jets

- Size of a variable-*R* jet depends on its transverse momentum, making these jets ideally suited for boosted decay topologies – separation between decay products of a heavy particle decreases with momentum. $R_0 \longrightarrow R_{eff}(p_{T,i}) = \frac{\rho}{p_{T,i}}.$
- Significant performance improvements are found with Variable-R jets for a number of discriminating variables.





- Can build Variable-*R* versions of the AntiKt (kt) and C/A algorithms.
- At high Pt, most of the jet Pt is contained within a dR smaller than the R=1 jet used in tagging.
- Using VR jets with smaller effective area reduces contaminations from PU/UE and ISR.



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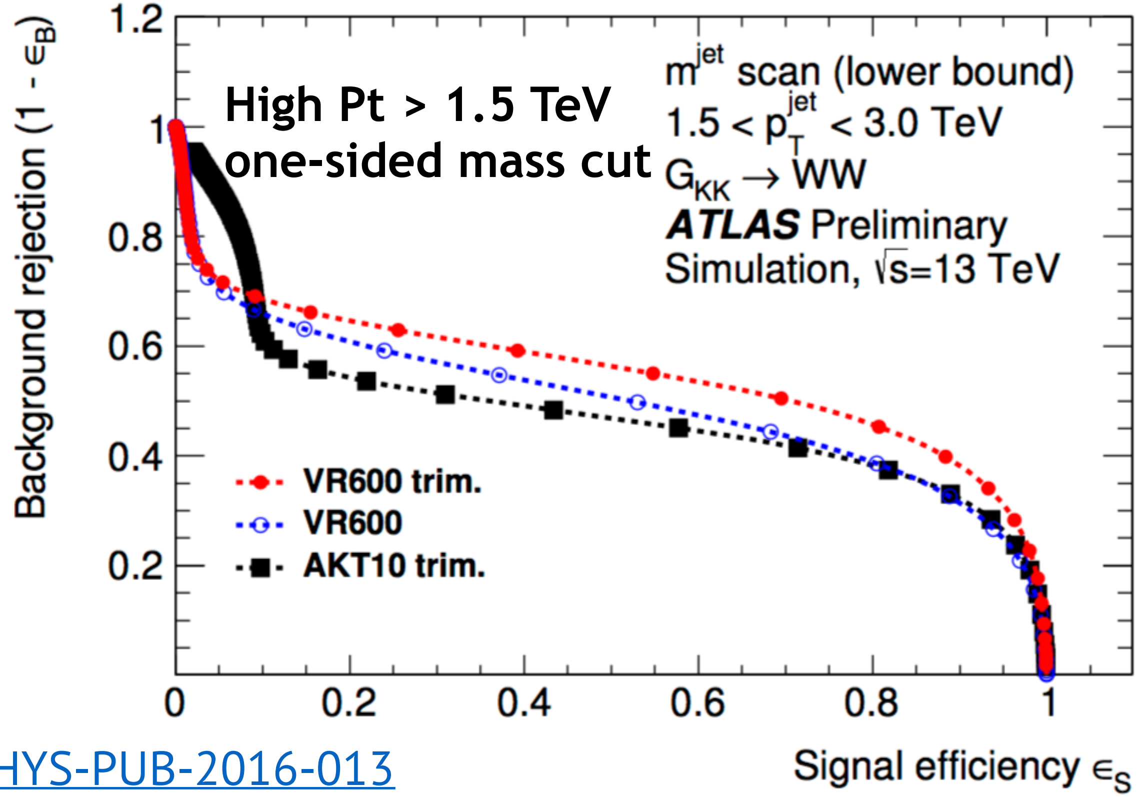
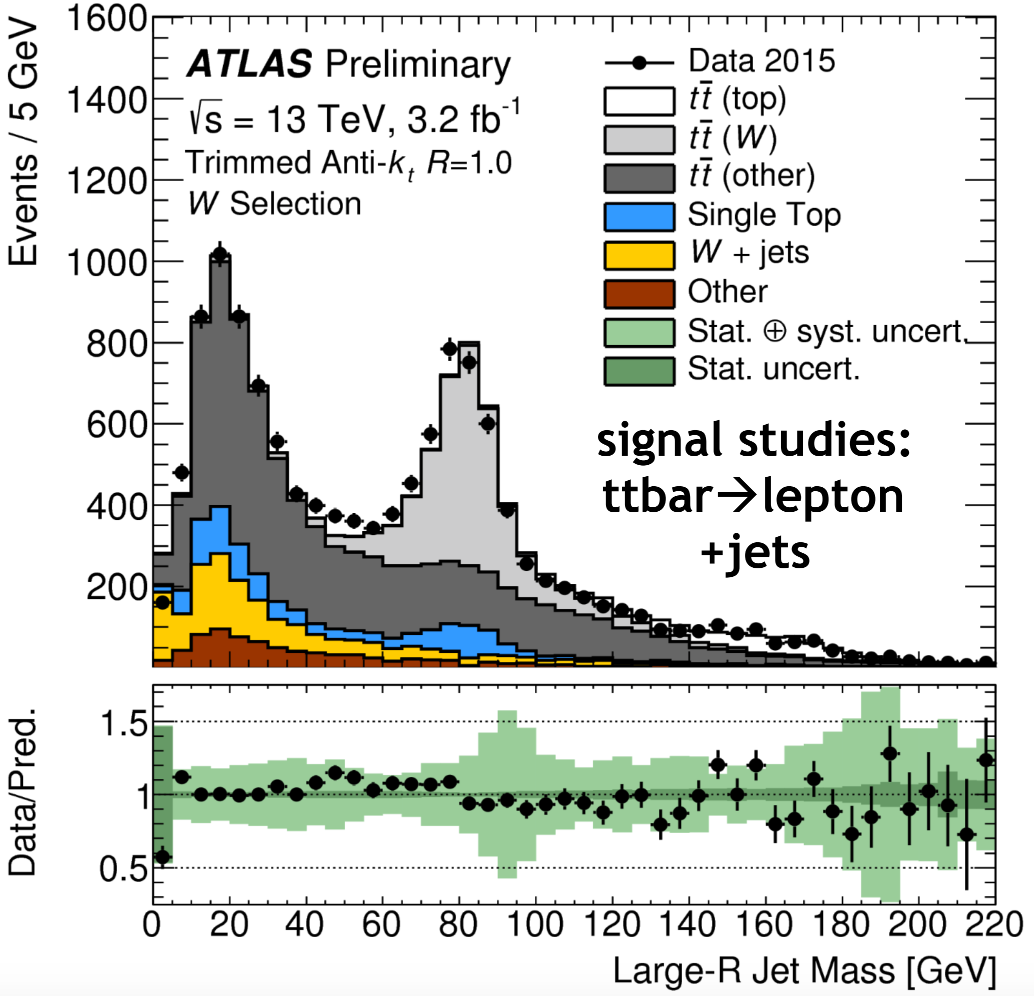


- Trimmed VR jets behave similarly to AntiKt R = 1.0 jets below 1 TeV, while outperforming AntiKt R = 1.0 jets for Pt > 1 TeV.
- With the two-sided mass window cut, variable-R jets has slightly worse performance than traditional AntiKt R=1.0 jets as a result of lower ISR contamination (high mass tail) for VR jets
  - Only small reduction (2-4%) in S/sqrt(B) for Pt > 1.0 TeV
- Notable performance improvements for substructure variables like first Kt splitting scale.

W-tagging in Data and MC: jet mass spectrum

JETM-2016-005

Calorimeter jet mass spectrum for leading jet Pt in 13 TeV data and MC for signal efficiency (left) and background rejection studies (right)

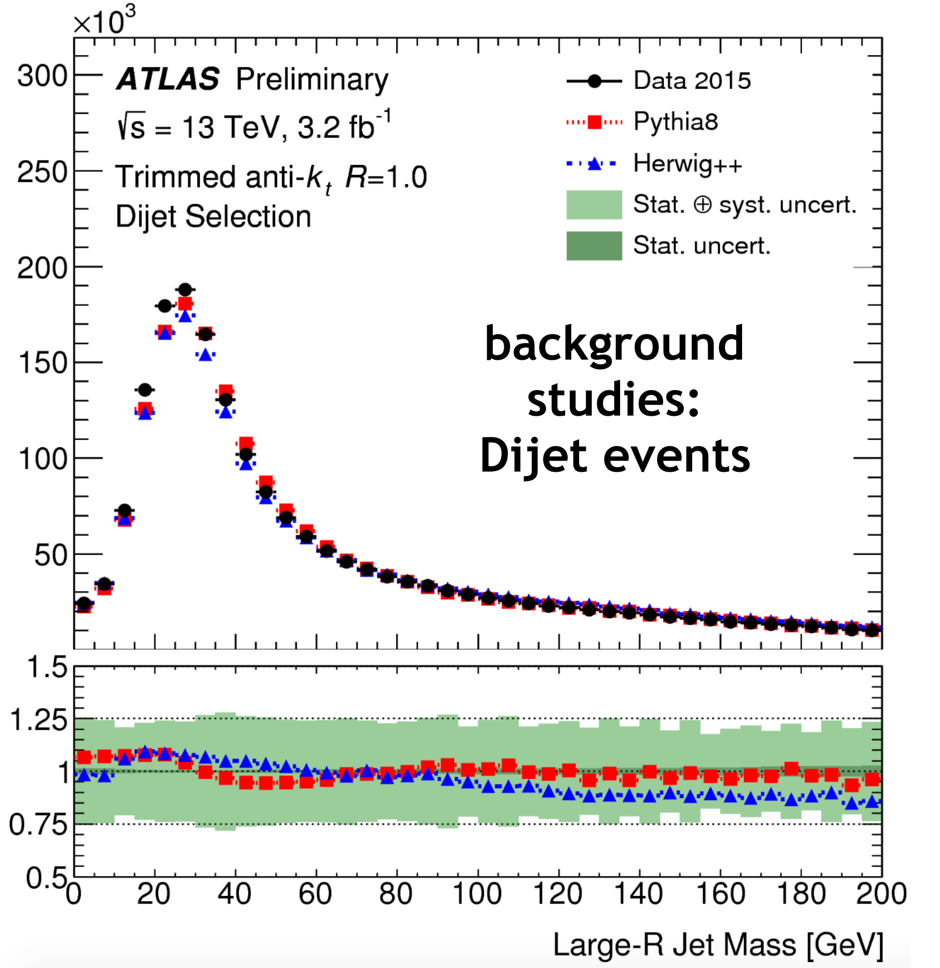


signal studies (left):

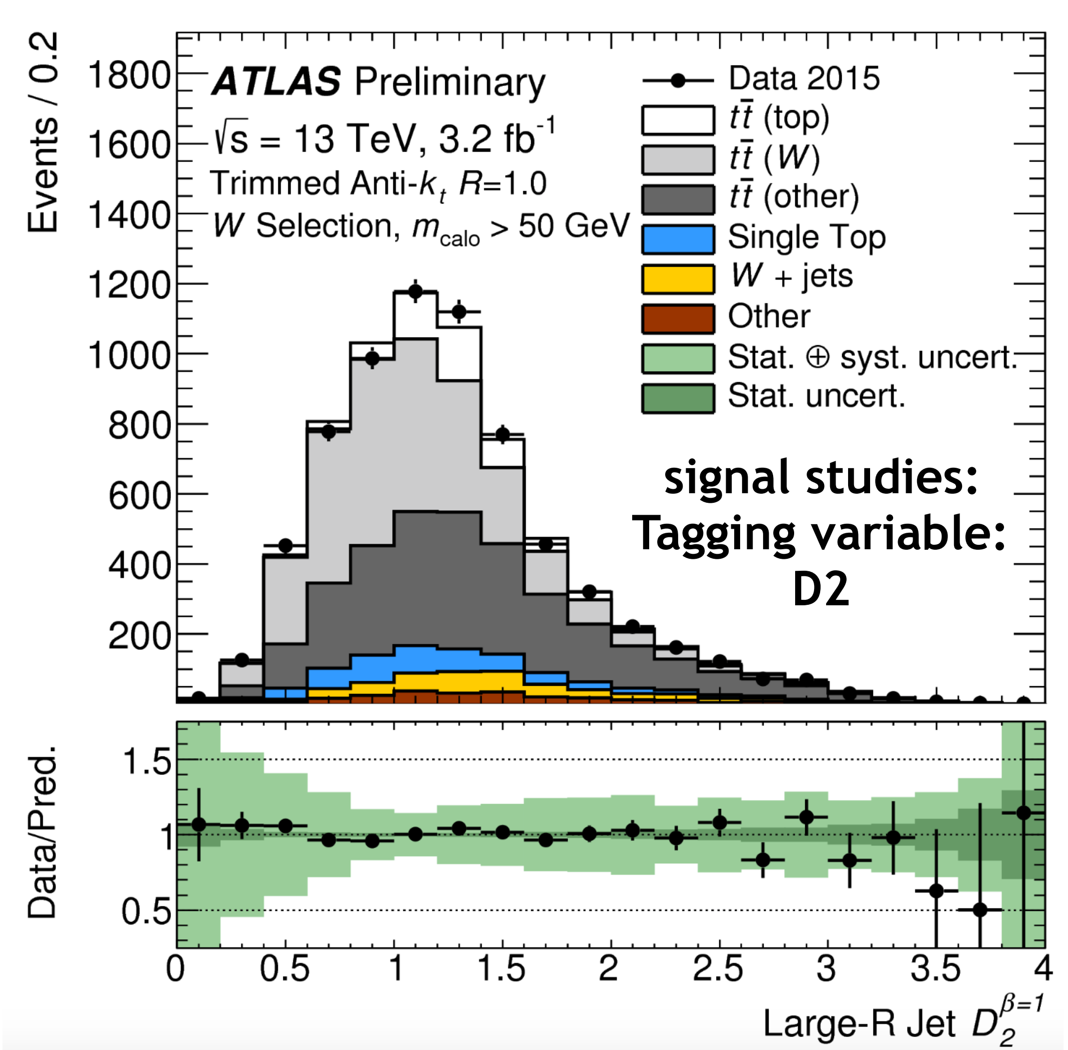
- ttbar sample is split into a "W -matched" part by requiring the decay products of W boson to be within the large-R jet.
- "top-matched" part requires the qqb particles from the top-decay to be within the large-R jet.

background studies:

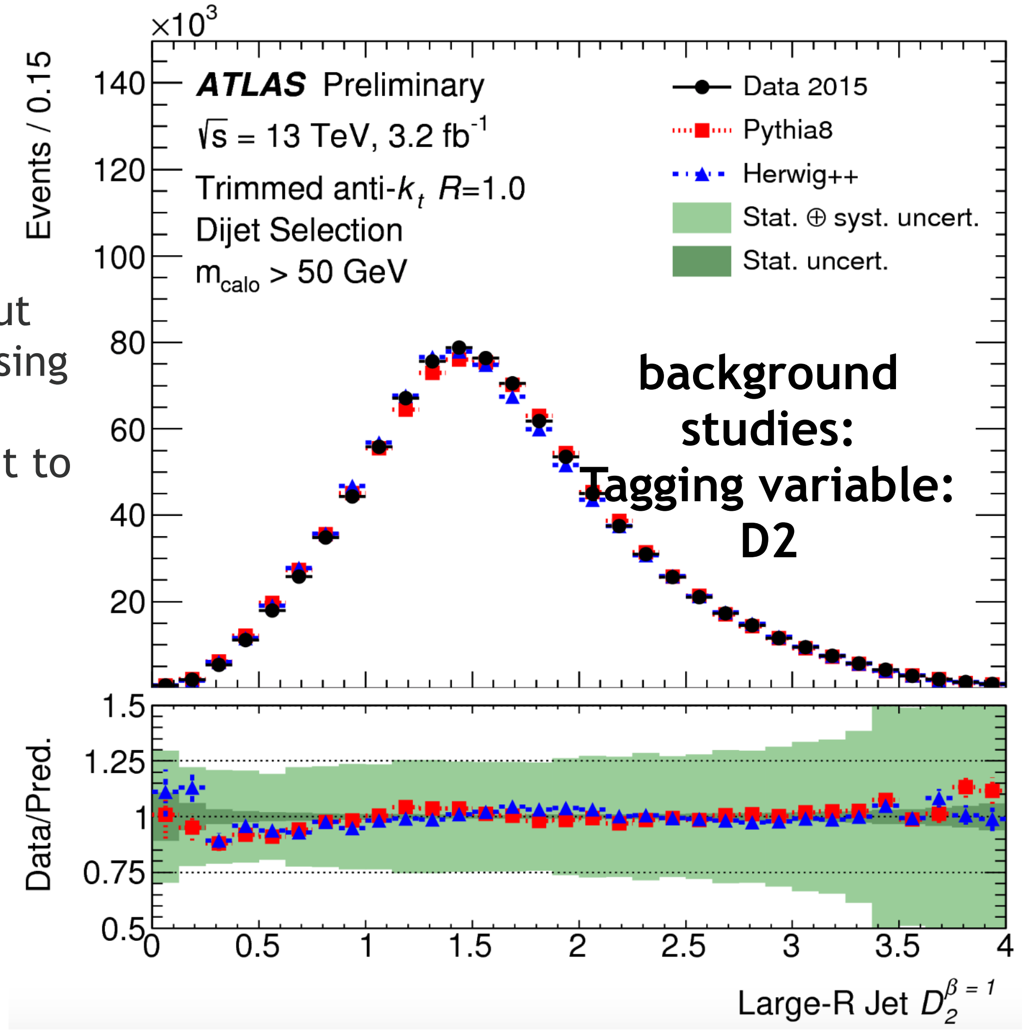
- large-R jet trigger requirement with ET > 360 GeV.
- At least 2 large-R jets with Pt > 200 GeV,
- leading jet Pt > 500 GeV



https://cds.cern.ch/record/219572



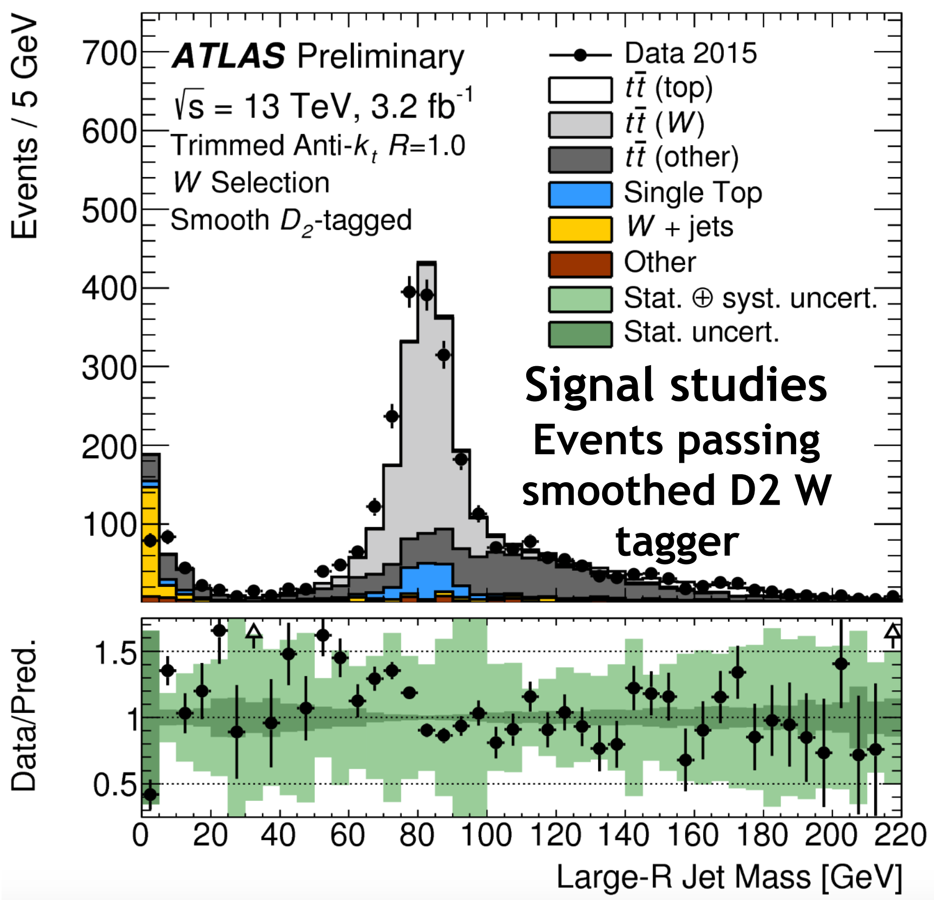
- D2 smoothed tagging algorithm applies a cut based on the jet pt using a fourth-order polynomial formula fit to define a smoothed selection.



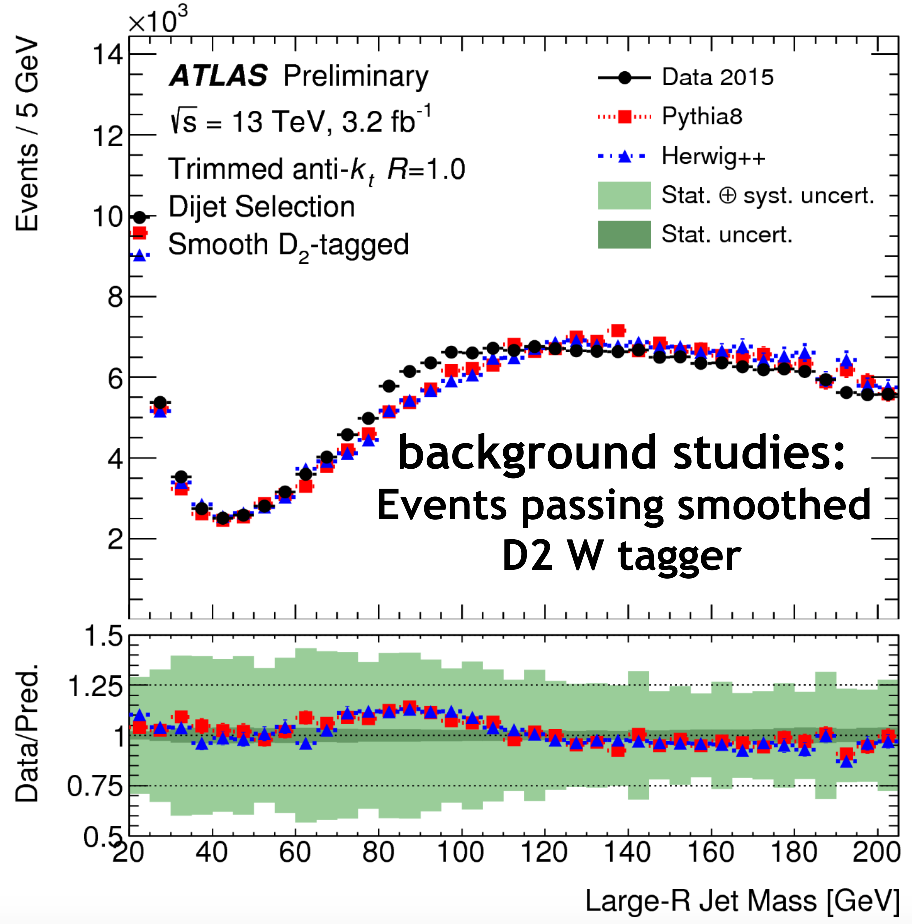
D2 observable in 13 TeV data and MC for signal efficiency (left) and background rejection studies (right)

W-tagging in Data and MC: events passing D2 tagger JETM-2016-005

D2-tagged events in 13 TeV data and MC for signal efficiency (left) and background rejection studies (right). 50% working point is shown.



- Systematic uncertainties are composed of:
- scale and resolution uncertainties on large-R jet energy, mass and substructure observables
- Ttbar modeling uncertainties on parton shower, hadronization model
- Initial-state and final-state radiation.
- Subdominant scale and resolution uncertainties on small-R jet energy and lepton kinematics



- Excess in plot on right around W mass is covered by systematics

Conclusions

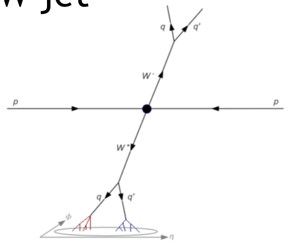
- Best performing grooming techniques and tagger variables from Run 1 studies have been studied and validated in Run 2.
  - grooming with AntiKt R=1.0 trimmed fcut=5%, Rsubjet=0.2 was best performing
  - tau21, C2 and D2 were best forming variables
- Early W- and Z-tagger results in Run 2 studied for medium and tight working points
  - Better background rejection for Z+jets overall
  - At low Pt, W-tagger has better background rejection with tagger+mass window cut selection.
- Track association to large R jet has shown to further help distinguish boson-jet signal and QCD jet background in the VVJJ analysis
- Variable-R jets have been studied for the first time as an alternate method for defining the boosted object compared to traditional methods, MC based studies:
  - Pt dependent jet radius expected to give better hold over pileup, comparison with R=1 groomed jet shows better performance at high Pt
  - VR jets worth investigating for W tagging: notable performance improvement in first kT splitting scale
- Smoothed D2 tagger for W-jet tagging has been studied in 13 TeV data and MC

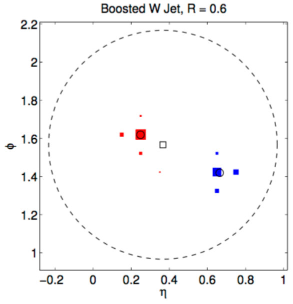
Backup

substructure variables: subjettiness

J. High Energ. Phys. (2011) 2011: 15.

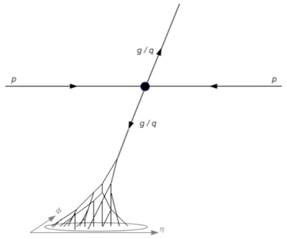
W-jet

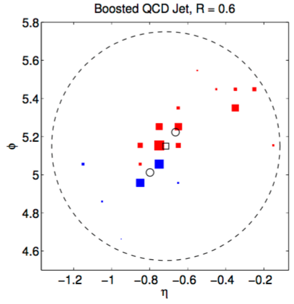




(a) subjettiness (b)

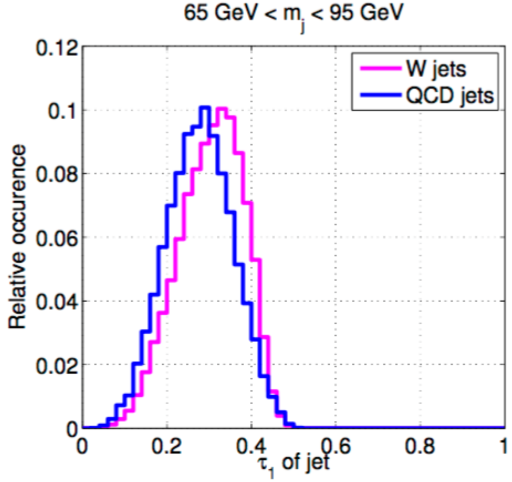
QCD-jet

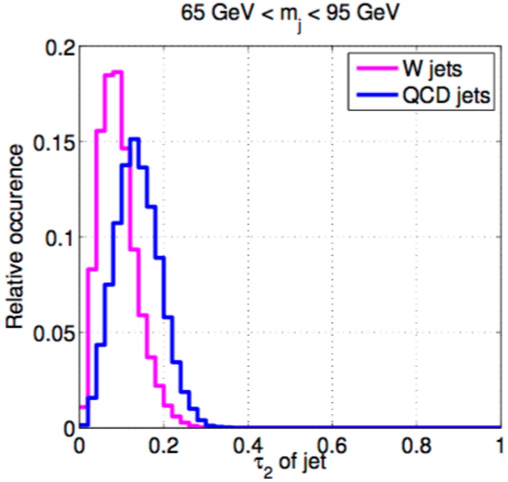


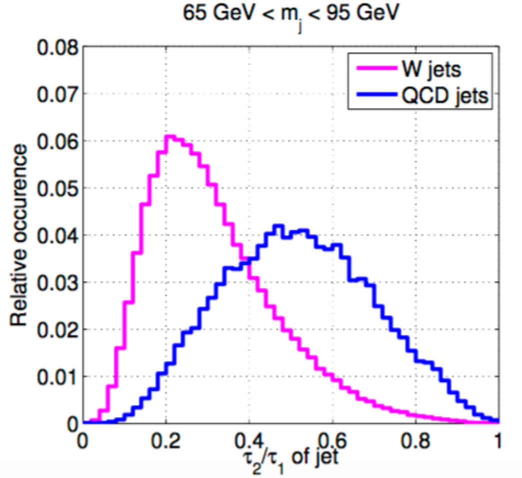


(c) (d)

N-subjettiness is an inclusive jet shape that offers a direct measure of how well jet energy is aligned into subjets, and is therefore an excellent starting point for boosted object identification.







- W-jet his typically composed of two lobes of energy while QCD-jet acquires invariant mass through multiple splittings
- open squares (right plots) indicate overall jet energy direction, open squares represent the subject energy directions
- discriminating variable $\tau 2/\tau 1$ measures the relative alignment of the jet energy along the open circles compared to the open square

- W-jet is expected to have lower values of tau2 but a QCD-jet can also have low value of tau2 (middle)
- A larger value of tau1 (left) is likely for a W-jet but a QCD-jet with a diffuse

spray of large-angle radiation can also have large tau1

- But QCD-jets with large values of tau1 typically have large values of tau2 as well. so we can use tau2/tau1 to discriminate between W-jet and QCD-jet.

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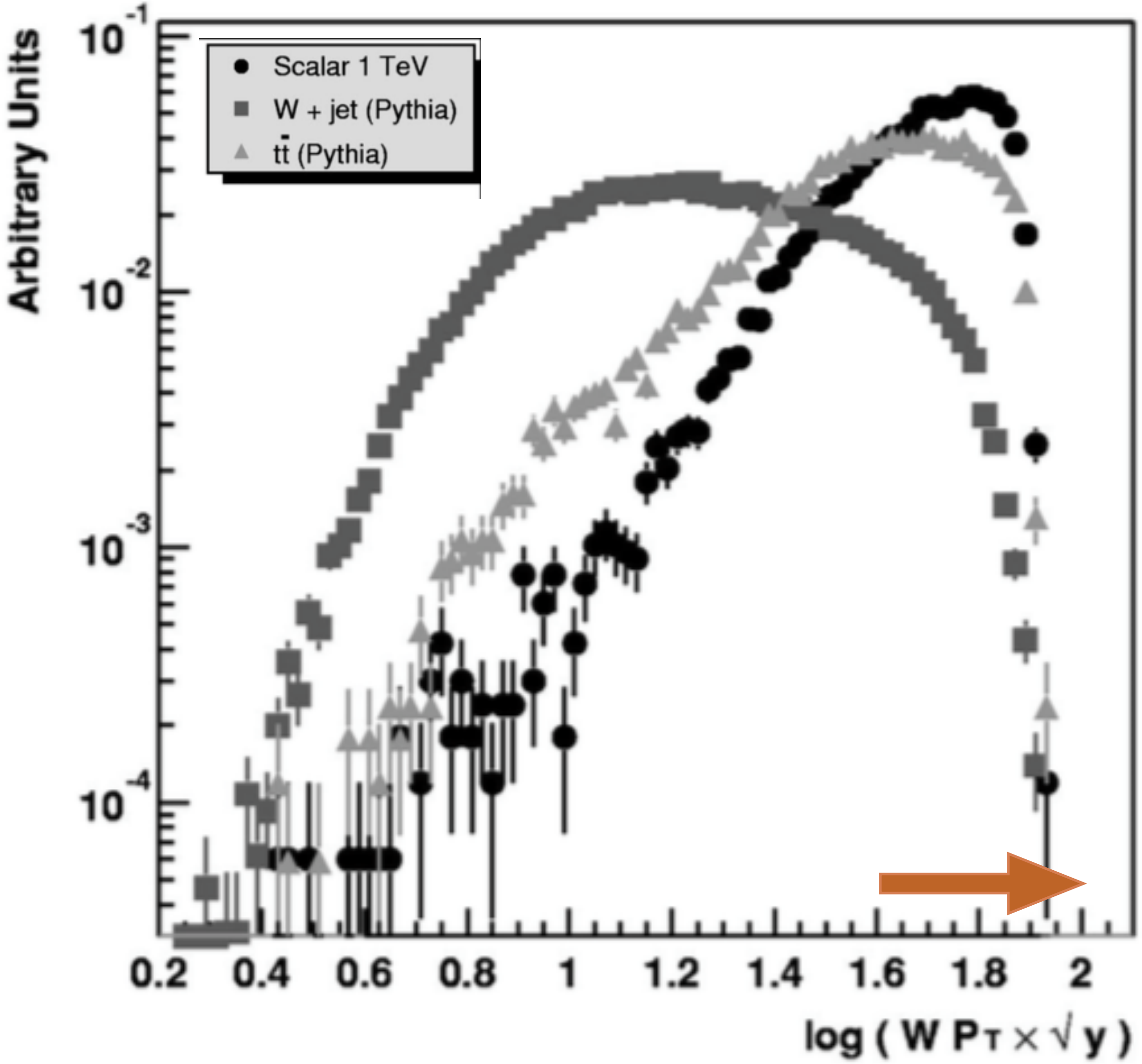
- Jet is split into subjets using reclustering with Kt algorithm
- extra information gained from the subjet decomposition are the y cut at which the subjets are defined and the four-vectors of the subjets.
- For a genuine W decay the expectation is that the scale at which the jet is resolved into subjects i.e. yPt^2 will be O(M^2_W).
- scale of the splitting is indeed high in the signal and softer in the W jets background, where the hadronic W is in general a QCD jet rather than a genuine second W.
- 1.6 < log(Pt y^(1/2)) < 2.0 is a powerful cut for reducing QCD W+jets background.
- effect on the t¯t background, which more often contains two real W bosons, is less marked.

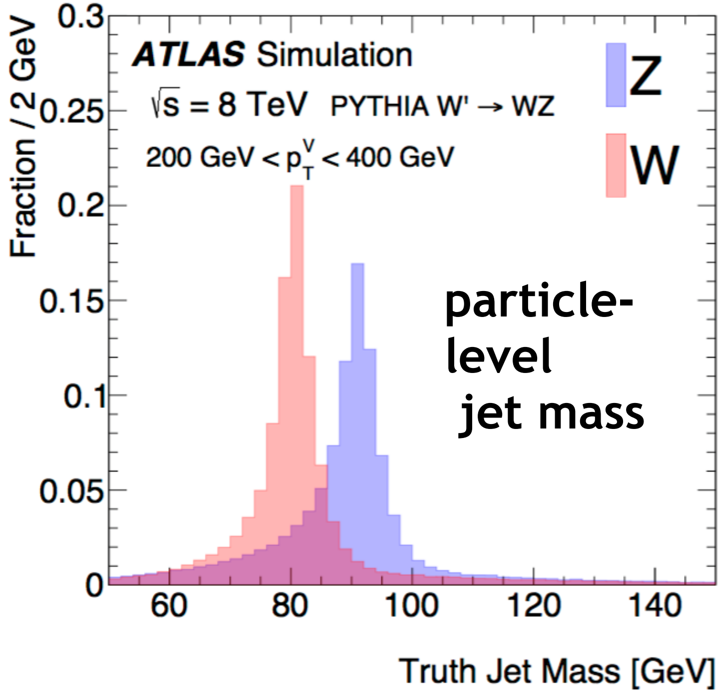


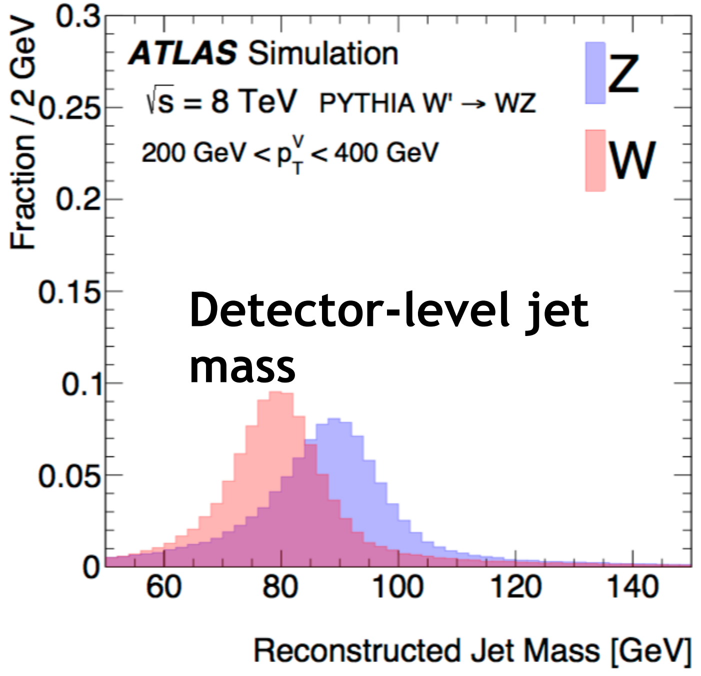
distribution of log(pT y^(1/2))

Distinguishing W-jet and Z-jet (1)

CERN-PH-EP-2015-194

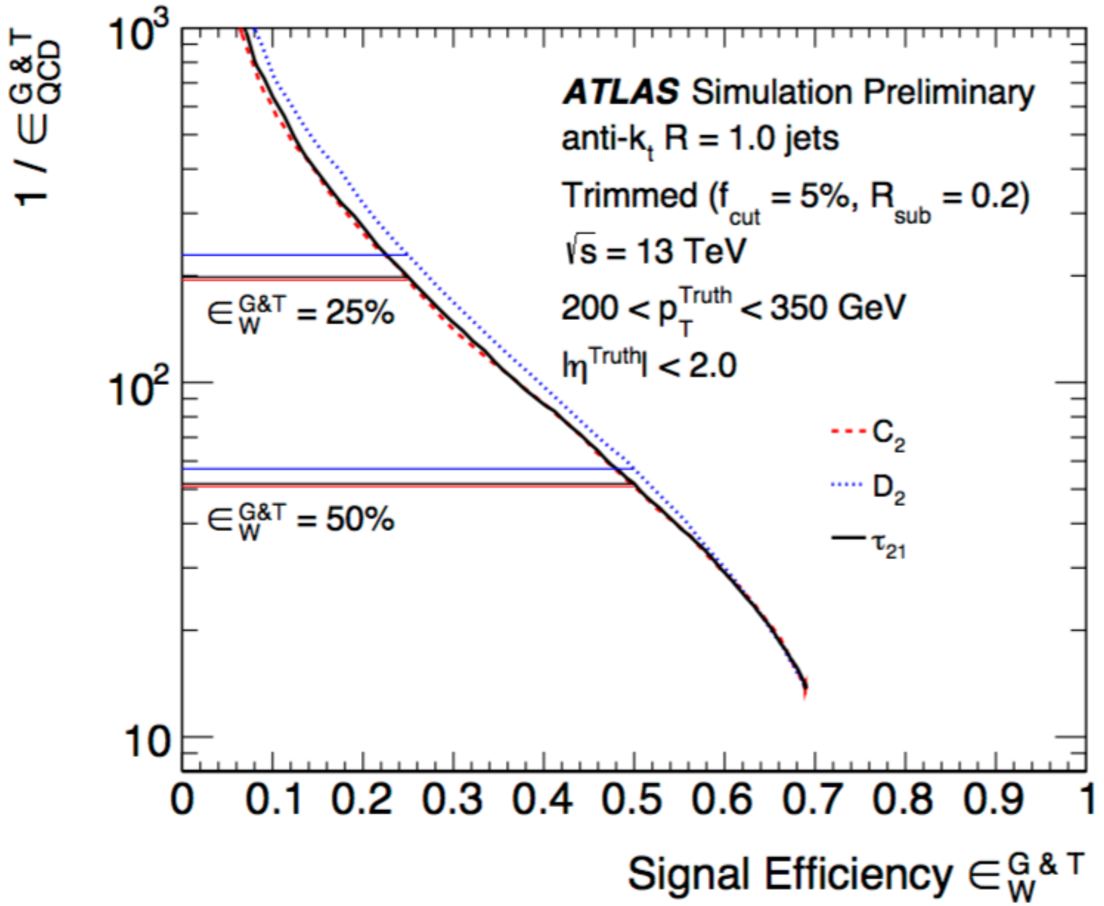
- W boson can radiate a Z boson making the separation challenging.
- Differentiating features: mass, charge and branching ratios.
- Differences in production XS and subtle differences in differential decay.
- Variables considered
  - Jet mass – sensitive to boson mass
  - Jet charge – sensitive to boson charge
  - B-tagging discriminant – sensitive to heavy flavor decay branching fractions of the bosons

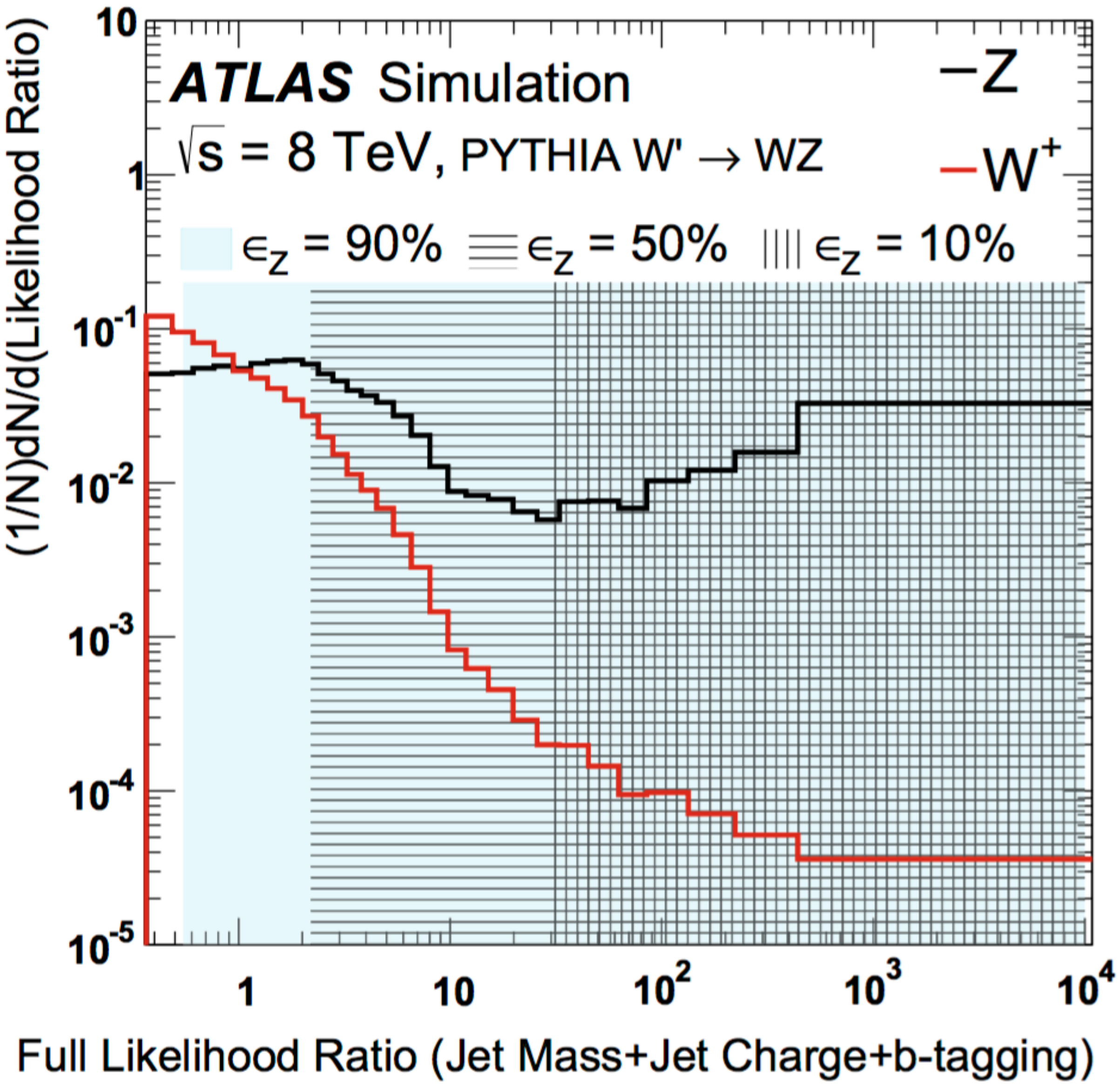




Despite resolution worsening at detector level, the jet mass is still a useful variable for distinguishing between W- and Z-jet

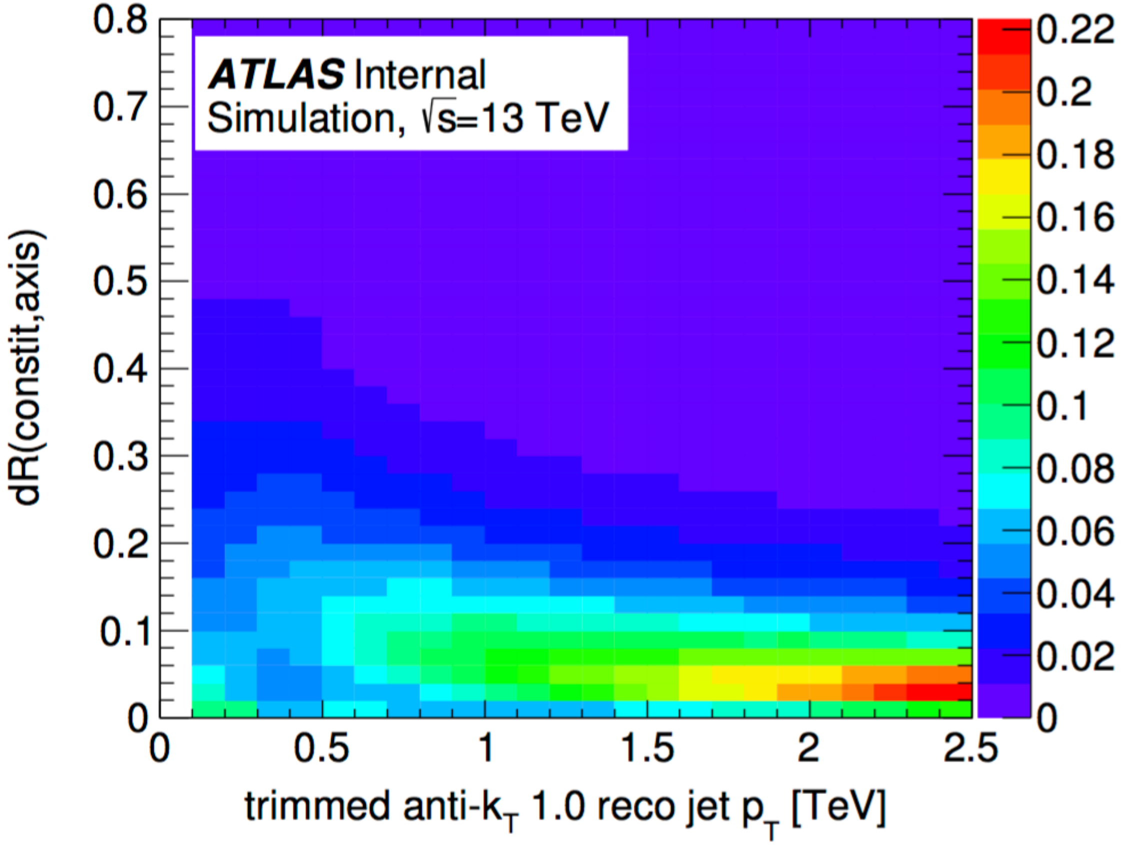
Systematic uncertainties on efficiency



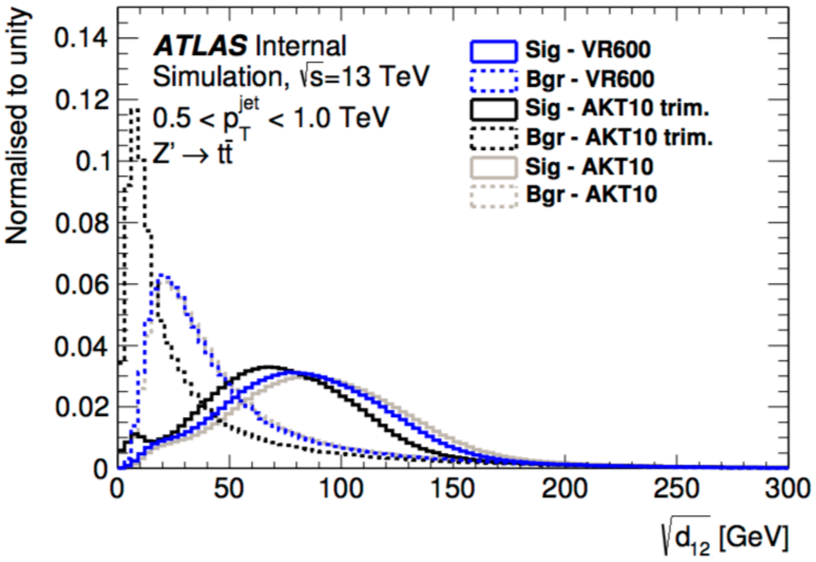


Tagging using variable-R jets

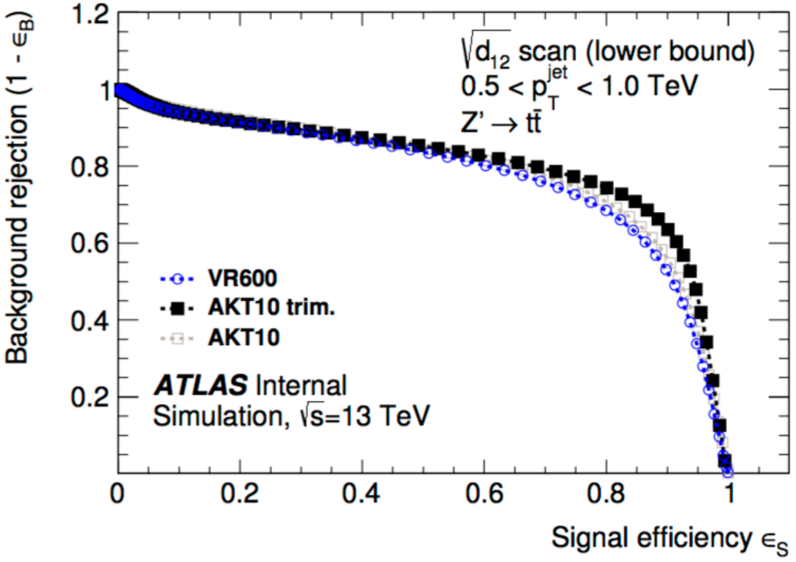
- Size of a variable-*R* jet depends on its transverse momentum, making these jets ideally suited for boosted decay topologies – separation between decay products of a heavy particle decreases with momentum
- Significant performance improvements are found with Variable-*R* jets for a number of discriminating variables, most notably the jet mass



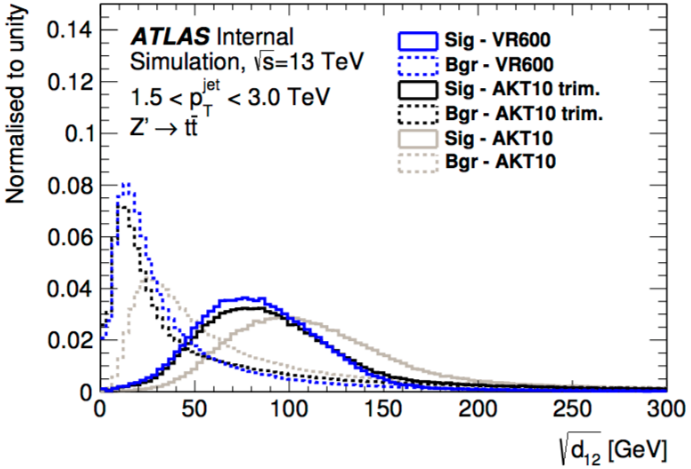
- Can build Variable-*R* versions of the anti-*k*T, the C/A and the *k*T algorithm.
- At high pT, most of the jet constituents are at very small dR values with respect to the jet axis



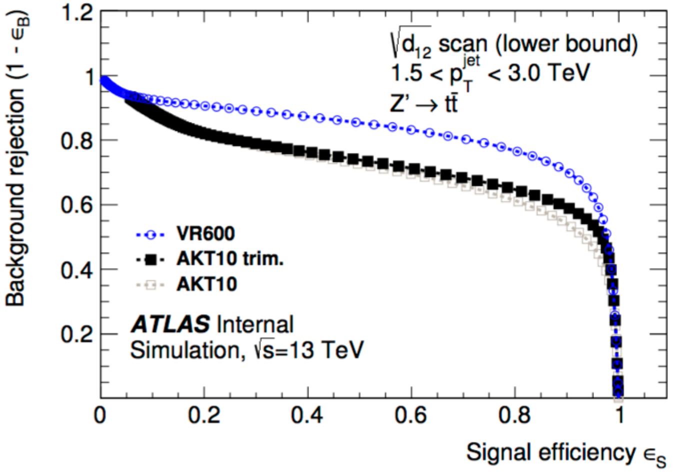
(a) 0.5 TeV $< p_T^{jet} <$ 1.0 TeV



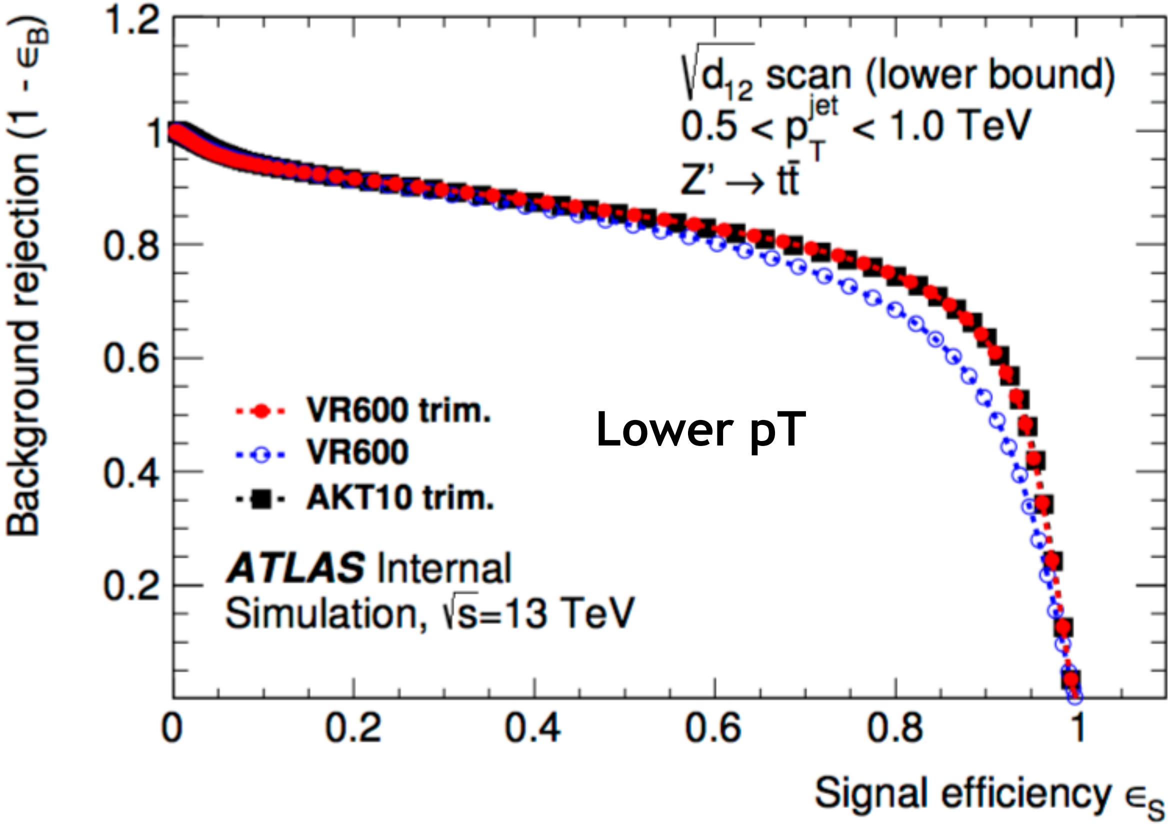
(b) 0.5 TeV $< p_T^{jet} <$ 1.0 TeV

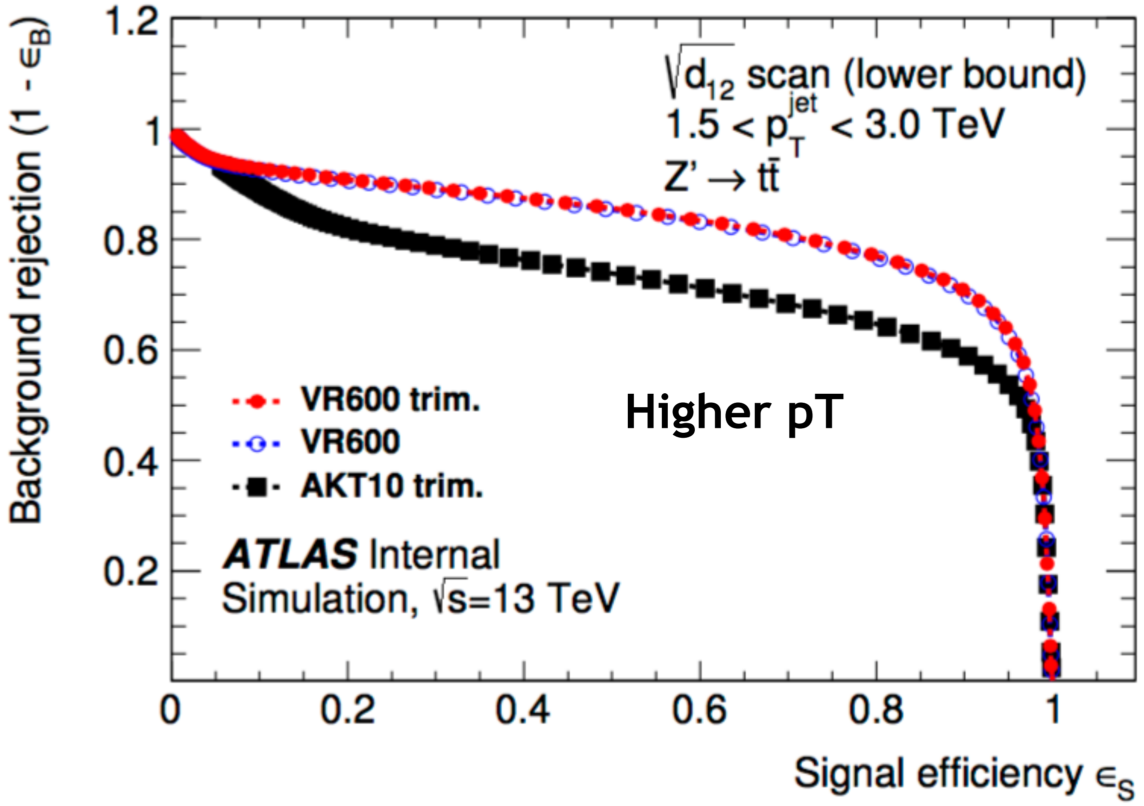


(e) 1.5 TeV $< p_T^{jet} <$ 3.0 TeV



(f) 1.5 TeV $< p_T^{jet} <$ 3.0 TeV





- Trimmed VR jets behave similarly to AntiKt R = 1.0 jets in the low-Pt regime, while outperforming AntiKt R = 1.0 jets in the medium- and high-Pt regions.
- With the two-sided mass window cut, variable-R jets has slightly worse performance than the standard W-tagger.

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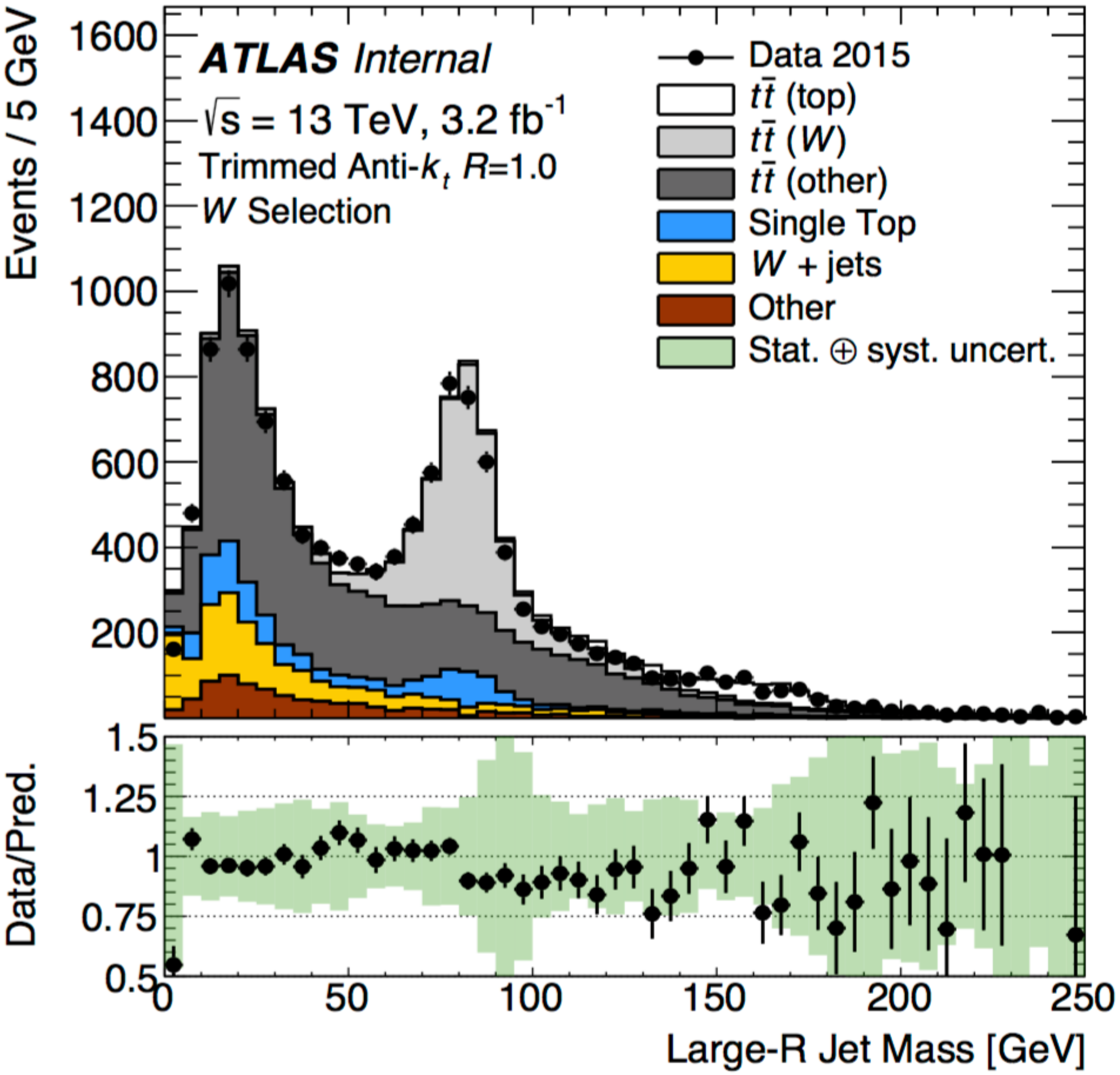
W-tagging in Data and MC: jet mass spectrum for signal



- Lepton+jets selection in ttbar events
- Leading-pT jet mass in 13 TeV data and MC simulation.
- Anti-kT R=1 jets calibrated at LCW+JES scale
- Trimmed jet: fcut=5%, Rsubjet=0.2
- Ttbar sample is split into a "W –matched" part by requiring the decay products of W boson to be within the large-R jet.
- "top-matched" part requires the qqb particles from the top-decay to be within the large-R jet.
- In addition to enhance purity of jets matched to a W boson, the events is required to have a R=0.4 b-tagged jet but outside the large-R jet cone.
- Systematic uncertainties are composed of
  - scale and resolution uncertainties on large-R jet energy, mass and substructure observables
  - Ttbar modeling uncertainties on parton shower, hadronization model
  - Initial-state and final-state radiation.
  - Subdominant scale and resolution uncertainties on small-R jet energy and lepton kinematics

https://cds.cern.ch/record/219572