# An infinite cone jet algorithm for identification of boosted $W/Z/H$

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# Outline

- Motivation
  - 'Fat jet' algorithms in ATLAS
  - Why implement just another one?
- The algorithm:
  - Lorentz invariant
  - Infinite cone
  - Automatic pileup/UE subtraction
  - No need for grooming of the reconstructed jet
- Results:
  - Tests on $W' \to WZ$ MC: signal efficiency vs. background rejection is $\simeq$50% vs. 1/1.5% for $350 < p_T^W < 500$ GeV, $|y_W| < 4.8$
  - Tests on $t\bar{t}$ data (13 TeV, $\sim 1$/fb)
- Summary

*As presented at Jet substructure and jet tagging meeting on Dec, 17: https://indico.cern.ch/event/446073/*

# Motivation

- No need to reproduce arguments in favour of reconstruction of boosted $W/Z/H$ as a single 'fat' jet
- A number of state-of-the-art 'fat jet' algorithms are routinely used in ATLAS (for exotics, high mass $VV$ production, etc.). A typical chain includes jet reconstruction with a wide cone, removal of soft components from UE, ISR, pileup (grooming) and construction of jet structure variables to discriminate between the two cases:
  - *color-neutral massive state* $\rightarrow q\bar{q} \rightarrow$ *fat jet* and
  - *colored combination of partons* $\rightarrow$ *fat jet*
- The existing algorithms typically involve several free parameters optimized on a case-by-case basis ( *cf., e.g., CERN-PH-EP-2015-204* ):
  - cone size $R \sim 1$ of the intital C/A or AntiKt jet
  - cone $R_{sub} \sim 0.15 - 0.3$ to find subjets in the fat jet, $f_{cut} \sim O(5\%)$ to remove soft constituents with $\frac{p_T^{subjet}}{p_T^J} < f_{cut}$ *(trimming)*
  - $R_{cut}$ and $z_{cut}$ in *pruning*: drop softer constituent in a pair-wise reclustering if $\Delta R_{12} > R_{cut}\frac{2M_J}{p_T^J}$ or $\frac{p_T^{(2)}}{p_T^{(1+2)}} < z_{cut}$
  - momentum balance $y_{12}$ and mass-drop fraction $\mu_{12}$ in *split-filtering*, $\sqrt{y_{12}} = \frac{\min[p_T^{(1)}, p_T^{(2)}]}{m^{(1+2)}}\Delta R_{12}$, $\mu_{12} = \frac{\max[m^{(1)}, m^{(2)}]}{m^{(1+2)}}$: while declustering the initial C/A jet, drop lower mass constituent if $\sqrt{y_{12}} < \sqrt{y_{min}}$ or $\mu_{12} > \mu_{max}$

# Motivation: why implement one more algorithm?

- Reconstruction of *color neutral* $X \rightarrow$*jets* must be **Lorentz invariant**:
  - an interference between radiation off initial $X \rightarrow q\bar{q}$ legs and off other color-disconnected legs is suppressed
  - properties of the hadronic final state in *color neutral* $X \rightarrow q\bar{q}$ depend only on $m_X$ and its polarization, there's no dependence on $p_T(X)$
  - $\Rightarrow$ no fixed cone, use only invariant combinations of objects' momenta to form the metrics for pair-wise object merging
- Unrelated **soft components (UE, pileup) are to be rejected in course of jet reconstruction**:
  - compare probability of occasional combination of two objects with the probability to produce them by splitting a single parent $\sim q \rightarrow qg$, $g \rightarrow gg$, $g \rightarrow q\bar{q}$
- Clustering history should follow the shower history
  - use known QCD splitting kernels as the metrics
- **Eliminate the need for grooming** on top of reconstruction, just use structure variables like $D_2$ to discriminate between $W/Z/H \rightarrow q\bar{q}$ and the QCD background
- **Minimize the number of free parameters**
- Shouldn't be too sophisticated, process specific and CPU consuming as shower deconstuction algorithms using global event topology *(cf., e.g., ATLAS-CONF-2014-003)*

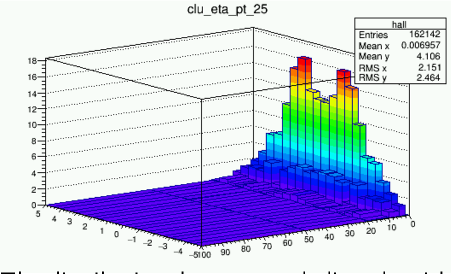
# The algorithm

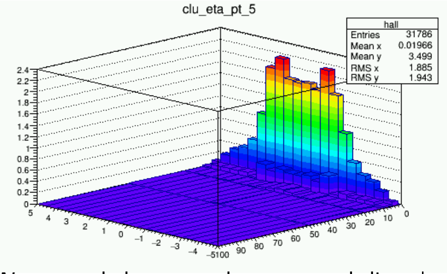
- Starting from `CaloCalTopoClusters` with $E_T^{clus} > 0.5$, 1, 2 GeV and $|\eta^{clus}| < 4.8$
- Information from Inner Detector is not used, except for the number of type=1,3 vertices to estimate the pileup in the given event
- 4-momenta of incoming partons estimated from $\Sigma\vec{p}^{clus}$ and $\Sigma\vec{p}^{\,\ell^{\pm}}$ also participate in the clusterisation (roughly speaking, to classify a part of the hadronic state as an ISR).
- For each pair of objects (single clusters or already merged clusters), a probability of occasional combination $w_{comb}$ (when at least one of the objects comes from pileup+UE with the known density estimated from $N_{vtx1,3}$ and hence with the known probability $w_b$ for the given cluster to originate from pileup+UE) is compared to a probability $w_{rad}$ to obtain this pair by splitting a common parent. If $w_{comb} > w_{rad}$ then the pair is ignored, otherwise the pair is added to the list of candidates for merging. The pair with a maximum $w_{rad}$ weight is merged and assigned a probability to come from signal $w_s = 1-$*probability to come from pileup+UE* from the pair's constituent with a maximum $w_s$ ($w_s$ calculation details are on the next slide).
- Objects with 4-momentum $Q$ such that $\sqrt{|Q^2|} > Q_{max} = const \cdot M_W$, where $const = 0.1 - 1$ is a free parameter, are excluded from further merging *($|Q^2|$ is used instead of a mass as incoming partons also undergo mergings with final state objects which give $Q^2 < 0$.)*

# The algorithm: pileup estimate

Density of topoclusters from pileup can be estimated for the known $N_{vtx1,3}$.

$N_{vtx1,3} = 25$  The normalization is clusters per $(p_T, \eta)$ bin per event  $N_{vtx1,3} = 5$




The distribution does not scale linearly with $N_{vtx1,3}$ and thus must be measured directly in `MinBias` events for each $N_{vtx1,3}$. For pileup estimation in the given event, it's convenient to divide $\phi$ plane into four sectors:

- One centered in $\phi$ at the maximum of $E_T$ density, $\phi_0 = \sum_{clus} p_T^{clus}\phi^{clus} \Big/ \sum_{clus} p_T^{clus}$ and with the half-width $\sim$ leading jet $\phi$ half-width:
  $$\Delta(\phi - \phi_0)^2 = \sum_{clus} p_T^{clus}(\phi^{clus} - \phi^0)^2 \Big/ \sum_{clus} p_T^{clus}$$
- The rest of $\phi$ space is divided in three equal bins.

# The algorithm: pileup vs. signal probabilities

Given an expected value $b$ of pileup/UE clusters in $(\Delta p_T, \Delta\eta, \Delta\phi)$ bin, actually finding there $n \geq 1$ clusters implies a modified probability for a single cluster to originate from pileup/UE:

$$w_b = \frac{b}{n} \frac{1 + b + ... b^{n-1}/(n-1)!}{1 + b + ... b^n/n!} ,$$

and hence the probability to originate from the signal $w_s = 1 - w_b$. A probability of an occasional combination of two objects (1) and (2), $w_{comb} = 1 - w_s^{(1)} w_s^{(2)}$, has to be compared with the probability to obtain (1) a (2) by splitting a common parent with 4-momentum $Q = p^{(1)} + p^{(2)}$ *(cf. well known QCD splitting kernels,* ▸ more on the metrics *)*:

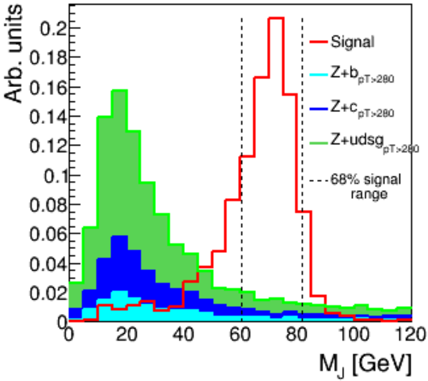
$$w_{rad} \sim \max[w_s^{(1)}, w_s^{(2)}] \times \frac{\alpha_S(Q^2)}{\pi} \cdot C \frac{Q_0}{p_0^{(2)}} \frac{p_T^{(2)} \Delta p_T^{(2)}}{Q^2} \Delta\eta^{(2)} \frac{\Delta\phi^{(2)}}{2\pi}$$

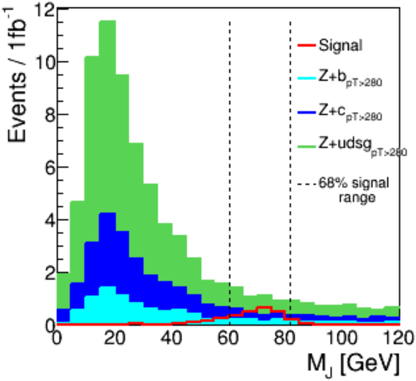
If $w_{rad} < w_{comb}$ then skip the (1)+(2) pair, otherwise add the pair to the list of candidates for merging with a weight $w_{rad}$.
$C$ is an unknown color factor ($C_A$ for $g \to gg$, $C_F$ for $q \to qg$ ...) which has to be considered as a second free parameter of the algorithm as we ignore different color combinations. In what follows $C$ is fixed so that $\frac{\alpha_S(M_Z)}{\pi} \cdot C = 0.1$.

# The algorithm: step by step

1. Prepare a list of objects to merge: `CaloCalTopoClusters` + the two incoming partons with 4-momenta estimated from $\Sigma \vec{p}^{clus}$ and $\Sigma \vec{p}^{\,\ell^{\pm}}$
2. Define $(p_T, \eta, \phi)$ binning to have a meaningful probability, $w_b$, for any cluster to originate from pileup, given the known $N_{vtx1,3}$ in the event
3. Load pileup $(p_T, \eta, \phi)$ density collected in MinBias events with the same $N_{vtx1,3}$
4. Assign $w_b$ and $w_s = 1 - w_b$ to each cluster as explained on the previous slide.
5. For each pair of objects:
    1. Find a probability of occasional combination of objects (1) and (2), i.e. that at least one of them comes from pileup/UE, $w_{comb} = 1 - w_s^{(1)} w_s^{(2)}$
    2. Find a probability $w_{rad}$ to split a hypothetic common parent into objects (1) and (2), see the previous slide.
    3. If $w_{rad} < w_{comb}$ go to the next pair, else add (1)+(2) pair to the list of candidates for merging with a weight $w_{rad}$
6. Merge the pair (1)+(2) with a maximum $w_{rad}$ weight (if it exists) into a single object, assign to the latter a probability to come from the signal $w_s = \max[w_s^{(1)}, w_s^{(2)}]$; otherwise, there's nothing to merge, `STOP`.
7. If $|Q^2_{(1+2)}|^{1/2} > Q_{cut}$ then the merged object is considered a reconstructed jet and excluded from further mergings *(if (1) stems from an incoming parton then freeze (2) as an ISR jet and vice versa)*
8. if any unfrozen objects remain, go to '5'; `STOP` otherwise.

# MC tests: $W' \to Z(\mu\mu)W(\to hadrons)$, $M_{W'} = 1$ TeV




Signal: $W'(1\,TeV) \to Z(\mu\mu)W(q\bar{q})$ with truth W: $350 < p_T^W < 500$ GeV,

`mc15_13TeV.302221.MadGraphPythia8EvtGen_A14NNPDF23LO_HVT_Agv1_VcWZ_llqq_m1000`

Background: $Z + jets$, truth Z: $280 < p_T^Z < 500$ GeV

`mc15_13TeV.361*.Sherpa_CT10_Zmumu_Pt280_500_{CVetoBVeto,CFilterBVeto,BFilter}`

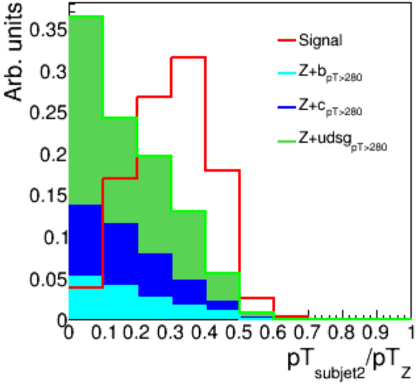
**Reco. selection:** STACO $\mu^+\mu^-$ with $p_T > 20$ GeV, $|\eta| < 2.47$, $71 < M_{\mu\mu} < 111$ GeV; max. $p_T$ Jet, $350 < p_T^J < 500$ GeV, $|y_J| < 4.8$

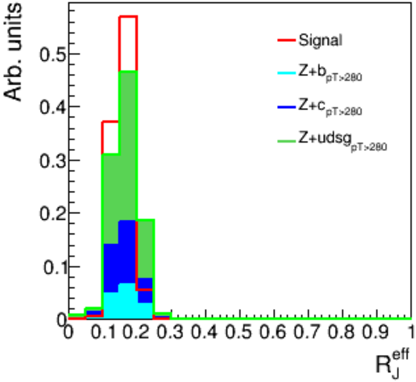
Jet $p_T$ | and pileup stability

# MC tests: $W'(1\,TeV) \to ZW$, subjet kinematics

Upon $M_J$ cut retaining 68% of the signal:

Pileup stability



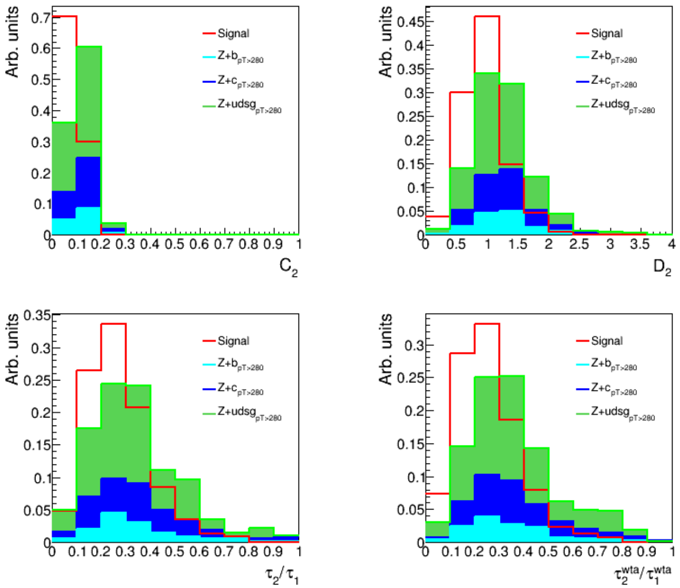




Step back: decluster fat jet into two subjets it was built from, use $\min[p_T^{subjet}/p_T^J] > 0.1$ to discriminate between QCD di-jets and di-jets from *longitudinally polarized W*

$$R_J^{eff} = \frac{\sum_{clus} p_T^{clus} \Delta R(clus, J)}{\sum_{clus} p_T^{clus}},$$

not informative after $M_J$ cut

# MC tests: $W'(1\,TeV) \to ZW$, $C_2^{(1)}$, $D_2^{(1)}$, $\tau_{21}^{(wta)}$



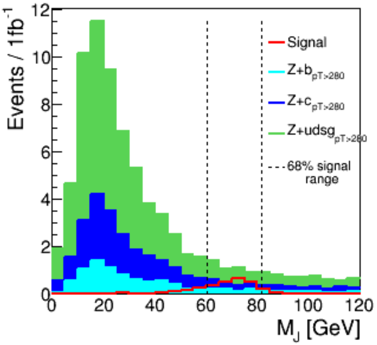

Less informative after $p_T^{subjet}/p_T^J$ cut.

▸ w/o $p_T^{subjet}/p_T^J$ cut

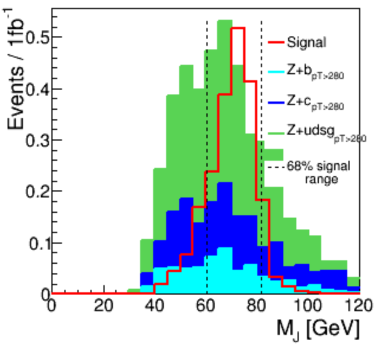
Still use $\tau_2^{wta}/\tau_1^{wta} < 0.37$ to further suppress QCD background. $\Rightarrow$

# MC tests: $W'(1\,TeV) \to ZW$, all cuts

Before substructure cuts:

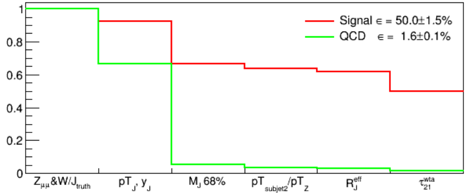



With all cuts:



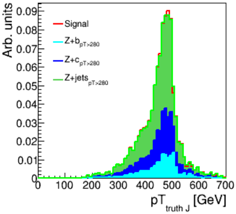

Cut flow ⇒

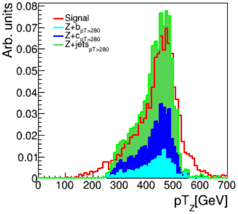
For signal selection efficiency $\epsilon^{sig} = 50\%$ one has $\simeq$ 60-fold background rejection.



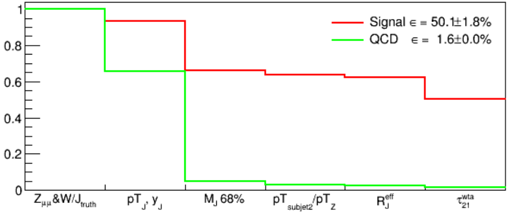
# MC tests: $W'(1\,TeV) \rightarrow ZW$ vs. $Z + jets$ with reweighted $Z$ and jet spectrum

Reco. selections: $350 < p_T^J < 500$ GeV, $|y^J| < 1.2$
*to compare with ATLAS results*
*CERN-PH-EP-2015-204*

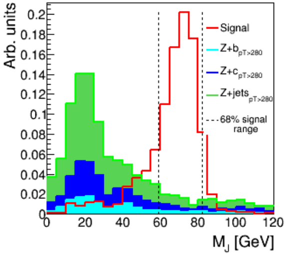


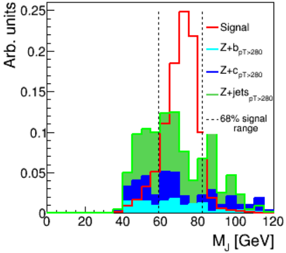

Cut flow: background rejection = 100%/1.6% for 50% signal efficiency ▸ Cf. 50/50 for groomed jets



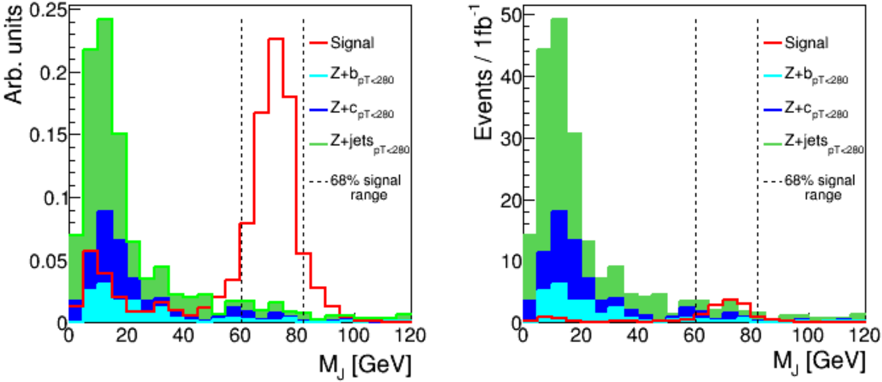

No cuts:




With structure cuts:



# MC tests: $W' \to Z(\mu\mu)W(\to hadrons)$, $M_{W'} = 500$ GeV




Signal: $W'(500 GeV) \to Z(\mu\mu)W(q\bar{q})$ with truth W: $200 < p_T^W < 250$ GeV,
`mc15_13TeV.302216.MadGraphPythia8EvtGen_A14NNPDF23LO_HVT_Agv1_VcWZ_llqq_m0500`

Background: $Z + jets$, truth Z: $p_T^Z < 280$ GeV
`mc15_13TeV.361*.Sherpa_CT10_Zmumu_Pt140_280_{CVetoBVeto,CFilterBVeto,BFilter}`

**Reco. selection:** STACO $\mu^+\mu^-$ with $p_T > 20$ GeV, $|\eta| < 2.47$, $71 < M_{\mu\mu} < 111$ GeV;
max. $p_T$ Jet, $200 < p_T^J < 250$ GeV, $|y_J| < 4.8$

Jet $p_T$ | and pileup stability

# MC tests: $W'(500 GeV) \to ZW$, subjet kinematics

Upon $M_J$ cut retaining 68% of the signal:

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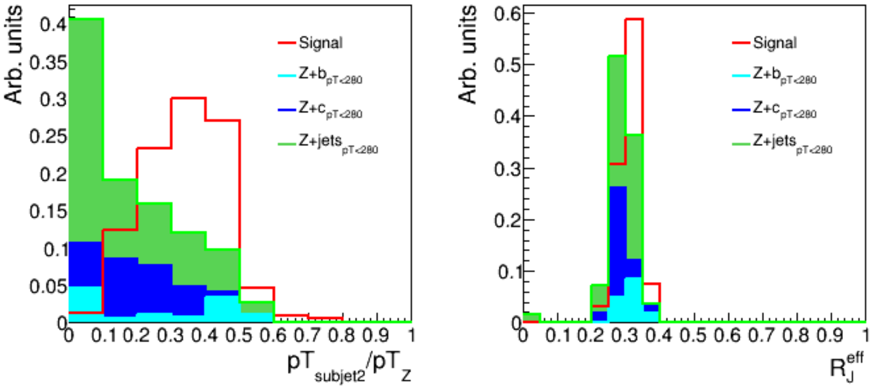
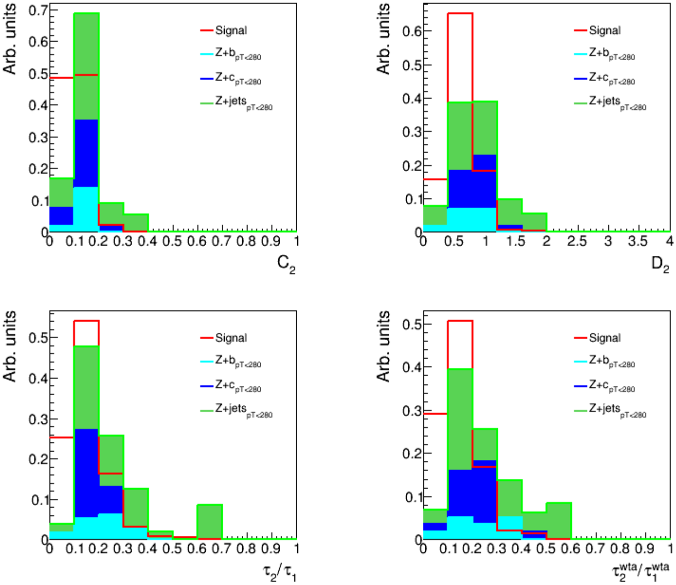



Step back: decluster fat jet into two subjets it was built from, use $\min[p_T^{subjet}/p_T^J] > 0.2$ to discriminate between QCD di-jets and di-jets from *longitudinally polarized W*

$$R_J^{eff} = \frac{\sum_{clus} p_T^{clus} \Delta R(clus, J)}{\sum_{clus} p_T^{clus}},$$

not informative after $M_J$ cut

# MC tests: $W'(500 GeV) \to ZW$, $C_2^{(1)}$, $D_2^{(1)}$, $\tau_{21}^{(wta)}$



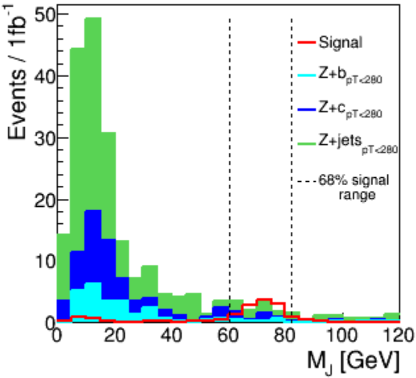

Less informative after $p_T^{subjet}/p_T^J$ cut.

▸ w/o $p_T^{subjet}/p_T^J$ cut

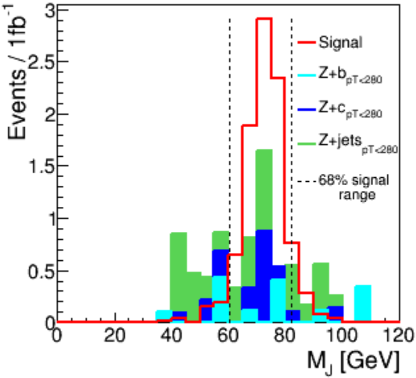
Still use $D_2^{(1)} > 0.8$ to further suppress QCD background. $\Rightarrow$

# MC tests: $W'(500\,GeV) \to ZW$, all cuts

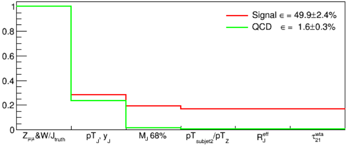
Before substructure cuts:




With all cuts:




Unresolved fat jet selection is inefficient for such a low $M(W')$. In a good portion of events the leading 'fat' jet is just one of 'thin' jets from $W \to jj$ or, even worse, its combination with a partially reconstructed second thin jet giving an intermediate mass. see relaxed cuts in backup

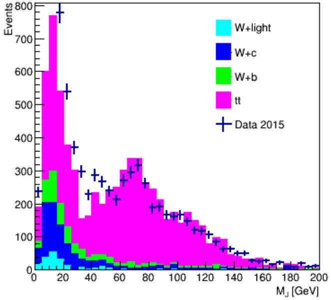


# $t\bar{t}$ 13 TeV data, $\mathcal{L}_{int} \simeq 1.4$/fb

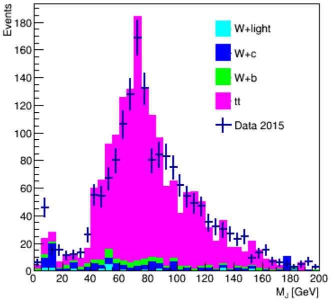
- **Data preselection:**
  =1 $\mu^{\pm}$: $p_T^{\mu} > 20$ GeV, $|\eta^{\mu}| < 2.47$, ptcone20/$p_T^{\mu} < 0.2$;
  $\geq 1$ AntiKt4EMTopoJets: $p_T^{jet} > 20$ GeV, $|\eta^{jet}| < 2.5$,
  MV2c20$> -0.5$;
  $\sum E_T^{calo} > 300$ GeV
  *(using a customized* EXOT11 *derivation)*
- **Data&MC selection:**
  $\mu^{\pm}$: ptcone20/$p_T^{\mu} < 0.01$, $\cos(\vec{p}_T^{\mu}, \vec{E}_T^{mis}) > 0.6$,
  $|\vec{p}_T^{\mu} + \vec{E}_T^{mis}| > 50$ GeV;
  $\geq 1$ AntiKt4EMTopoJets: $p_T^{jet} > 20$ GeV, MV2c20$> -0.44$;
  Leading fat jet: $p_T^J > 150$ GeV, $|y^J| < 4.8$
- **MC samples:**
  $W + jets$:
  mc15_13TeV.361*.Sherpa_CT10_Wmunu_Pt{0...500}_{CVetoBVeto,
  CFilterBVeto,BFilter}
  $t\bar{t}$:
  mc15_13TeV.410000.PowhegPythiaEvtGen_P2012_ttbar_hdamp172p5
  _nonallhad
- Selections were not optimised, still $W \to Jet$ peak sitting on a combinatorial background from $t\bar{t}$ is visible $\Rightarrow$

▸ $D_2^{(1)}$ and $\Delta R(J, b - jet)$ cuts

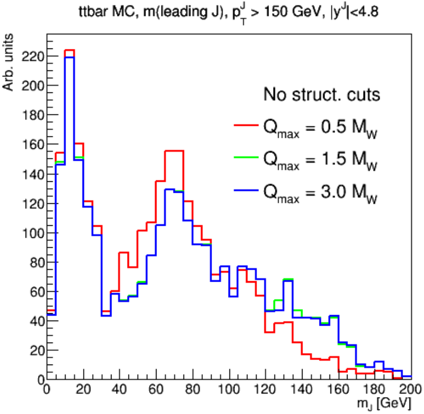
Raw fat jet selection:

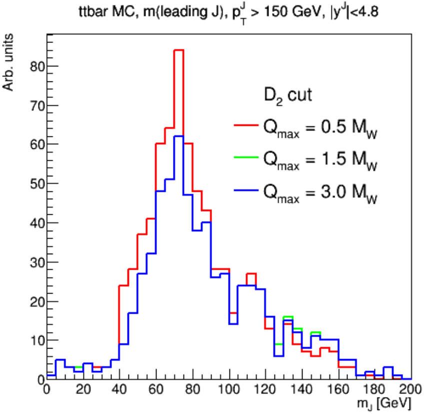



with $0.6 < D_2^{(1)} < 1.0$ ▸ cut



# Sensitivity to $Q_{max}$ (follow-up to the jet substructure meeting)



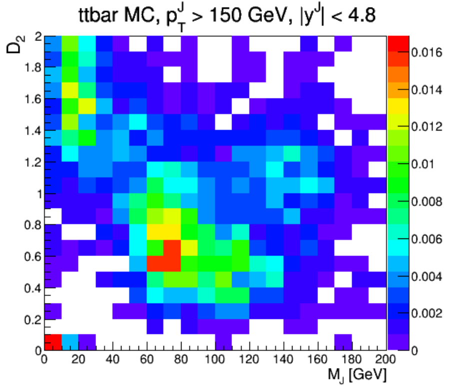

Do we really need $Q_{max} < m_J$, where $m_J \simeq M(W, Z, H, top, ...)$ is the mass we are targeting? From ▸ merging metrics it follows that a fat jet with mass $m_J$ is merged from its two sub-jets carrying $x_{1,2}$ fractions of jet momentum if $x_{1,2} p_T^J \gtrsim \frac{m_J^2}{\sqrt{\hat{s}}} e^{y_J - y_0}$, where $\sqrt{\hat{s}}$ and $y_0$ are the mass and the rapidity of the hard final state. For lower $p_T^J$ or $x_{1,2}$ the softer subjet is merged with the beam.

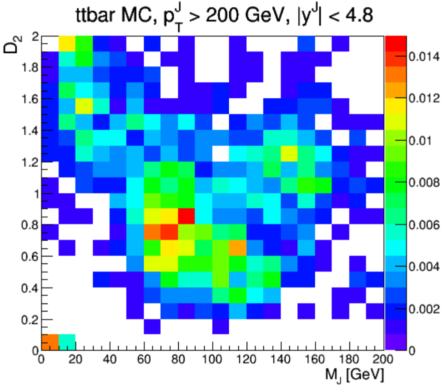
# Can we reconstruct $t$-quark as a single jet? ($Q_{max} = 3M_W$)

Yes, if

$$x_{subjet1,2}\, p_T^t \gtrsim \frac{m_t^2}{\sqrt{\hat{s}_{t\bar{t}X}}}\, e^{y_t - y_0} \;,$$

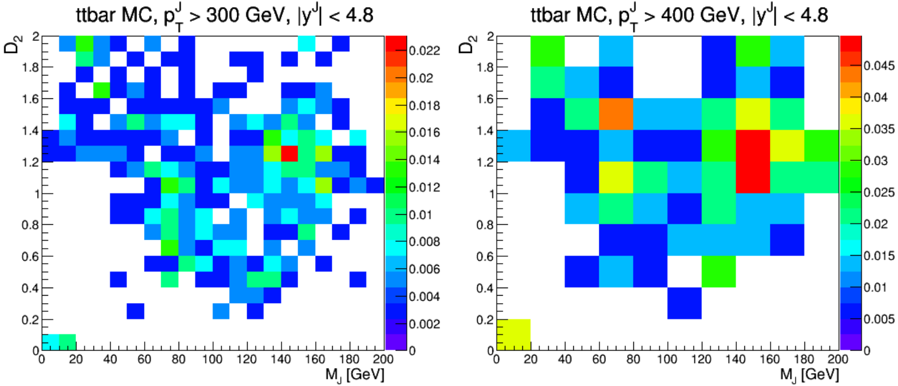
where $subjet_{1,2}$ is either $W$ or $b$-jet and $y_0$ is the rapidity of $t\bar{t}X$ system in the laboratory frame.




Larger maximum on the plots is $W$, in case $t \to Wb$ remains resolved.

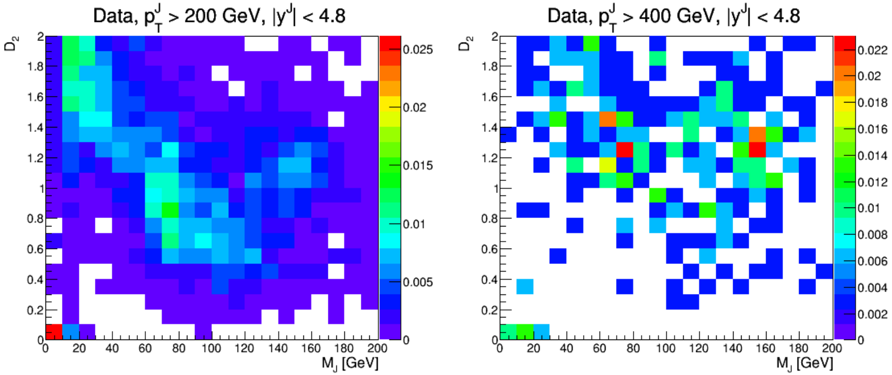
# Can we reconstruct $t$-quark as a single jet? *(continued)*




3-particle correlator $D_2^{\beta=1}$ can discriminate between $W \to jj$ and $t \to Wb \to 3j$ decays at $p_T^{W or t} \sim m_t$ (see previous slide).

Sub-jet mass in $t \sim J$

# Can we reconstruct $t$-quark as a single jet? *(DATA)*



# Summary

- Jet reconstruction algorithm with an infinite cone and 'in-flight' pileup/UE subtraction gives reasonable results for boosted $W \to jets$ $(M_W/p_T^W \ll 1)$ without grooming.
- For $W' \to ZW$, $350 < p_T^W < 500$ GeV, $|y_W| < 4.8$ the algorithm + $\tau_2^{wta}/\tau_1^{wta}$ cut yields 50% signal efficiency and QCD background rejection rate $\simeq 60$, comparable to C/A $R = 1.0, 1.2$ + grooming + substructure tagging used in ATLAS (cf. CERN-PH-EP-2015-204 )
- The algorithm was also tested on $t\bar{t} \to W^{\pm}bW^{\mp}\bar{b} \to \ell\nu b\bar{b}J$ '2015 data
- The algorithm is suitable for reconstruction of boosted $t$ as well, if supplemented by $D_2$ discrimination.
- The results are very preliminary.

Any feedback would be highly appreciated, thank you!

# Backup

# Metrics at $Q^2 \sim 1GeV^2$?

- Can one apply the QCD-motivated metrics at $Q^2 \sim 1$ GeV$^2$ i.e., more generally, to clusters rather than to "microjets" well separated in momentum space?
- The microjects must be constructed using a reasonable pileup/UE-proof algorithm which doesn't merge soft clusters at distances greater than the average distance between two pileup/UE clusters in the event, $\Delta R \gtrsim \left(N_{clus}^{PU+UE}/\Delta\eta \cdot 2\pi\right)^{1/2}$
- Two objects with 4-momenta $p$ and $k$ (let $k^0 \sim 1GeV \ll p^0$, $\Delta R(p,k) = R$) coalesce if

$$N_{rad}|_R \sim \alpha_S(p^0 k^0 R^2)\left[\frac{C}{\pi}\right]\frac{\Delta k^0}{k^0 R^2}\frac{\pi R^2}{2\pi} > \mu \frac{dN^{PU}}{dk^0 d\Omega}\Delta k^0 \pi R^2$$

$$\Rightarrow \alpha_S(p^0 k^0 R^2) \gtrsim 2\pi\mu \frac{dN^{PU}}{dk^0 d\Omega} k^0 R^2$$

$$\Rightarrow \frac{\alpha_S(p^0 k^0 R^2)}{2} \gtrsim N^{PU}\Big|_{\text{in } \pi R^2}$$

Let's freeze $\alpha_S$ for $Q^2 < 1GeV^2$ at $\alpha_S^{n_{flav}=5}(1GeV^2) \simeq \frac{1}{2}$ so that $\alpha_S < \frac{1}{2}$ at any $Q^2$ $\Rightarrow$ one needs $N^{PU}\big|_{\text{in } \pi R^2} \lesssim \frac{1}{4}$ to merge the clusters rather then treat the pair as a random PU+UE induced combination. In other words, if one expects $\ll 1$ PU+UE clusters in the given phase-space around a harder cluster but still finds a softer cluster there, then the two clusters are merged (and the combination is discarded otherwise) $\Rightarrow$ **The metrics is stable w.r.t. PU+UE and can be applied 'as is' for clusterisation of soft/collinear objects.**

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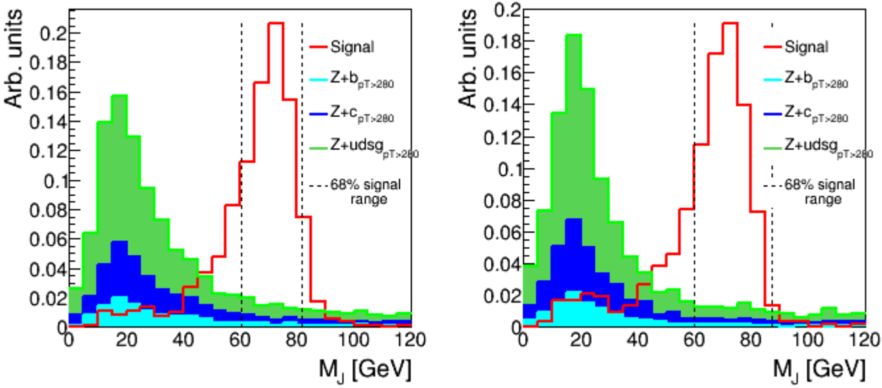
# MC tests: $W'(1\,TeV) \rightarrow ZW$, pileup stability




$\bar{\mu} = 15$ vs. $\mu > 20,\ \bar{\mu} \simeq 25$

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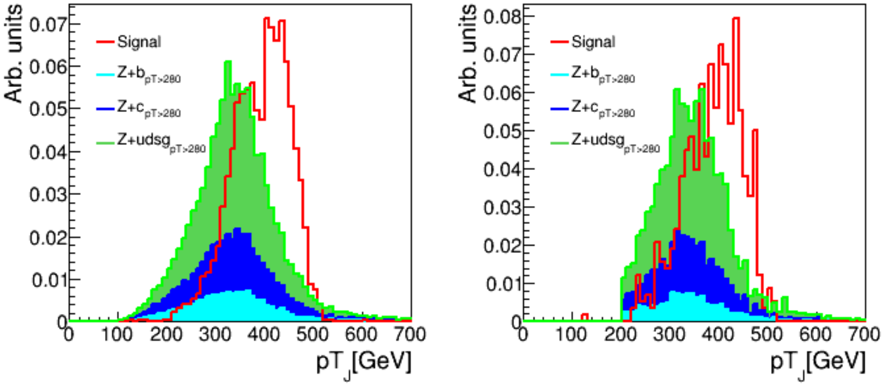
# MC tests: $W'(500\,GeV) \to ZW$, leading fat jet $p_T$




$\bar{\mu} = 15$ vs. $\mu > 20$, $\bar{\mu} \simeq 25$

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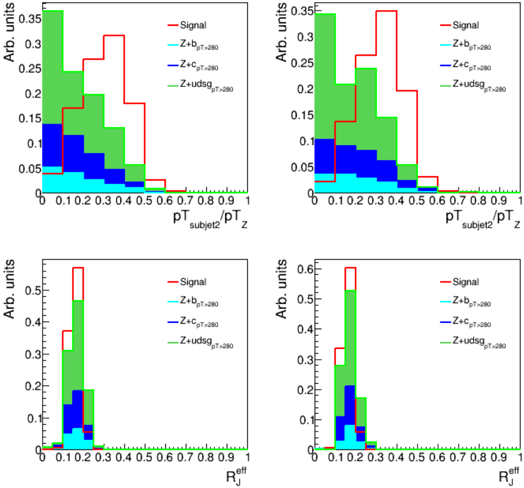
# MC tests: $W'(500\,GeV) \rightarrow ZW$, subjet kinematics vs PU




$\bar{\mu} = 15$ vs. $\mu > 20$, $\bar{\mu} \simeq 25$

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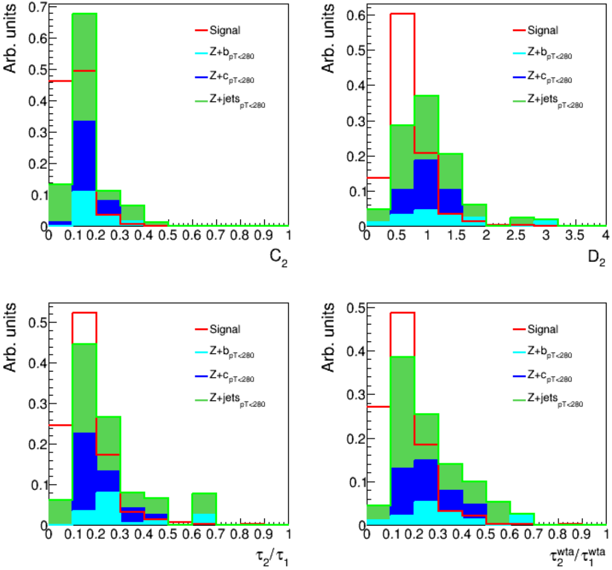
# $W'(500\,GeV) \rightarrow ZW$, $C_2^{(1)}$, $D_2^{(1)}$, $\tau_{21}^{(wta)}$ w/o $p_T^{subjet}/p_T^J$ cut

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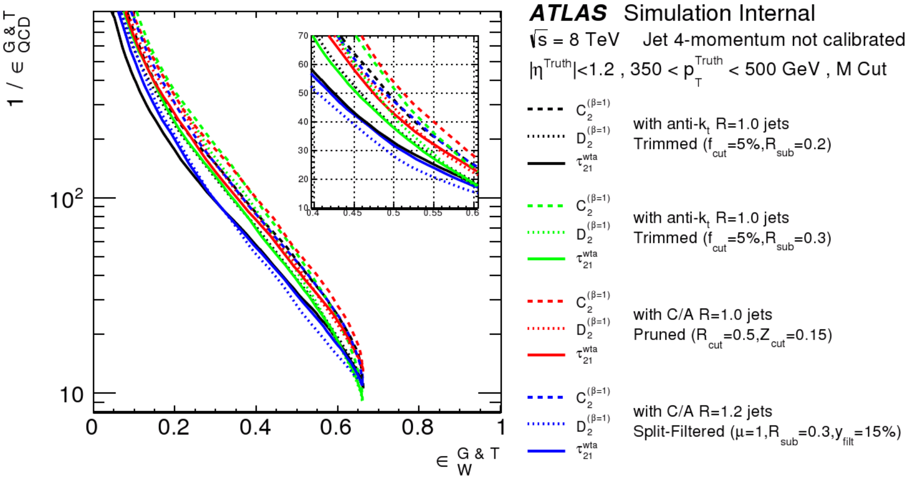
# $\epsilon_{signal}$ vs. $\epsilon_{QCD\ bkg}$, $350 < p_T(J) < 500$ GeV (*CERN-PH-EP-2015-204*)

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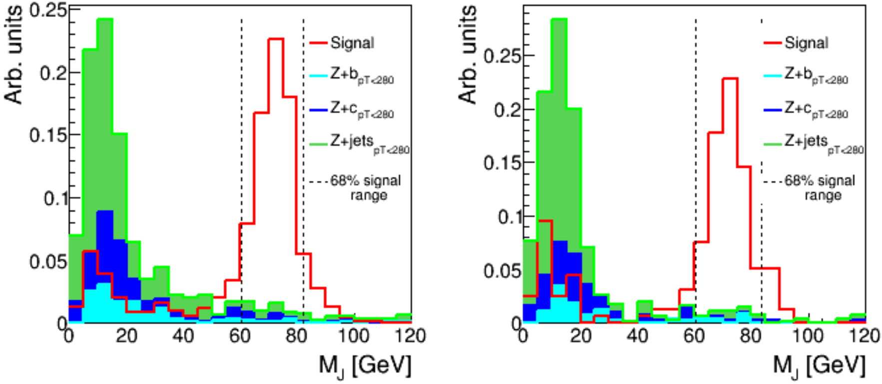
# MC tests: $W'(500\,GeV) \to ZW$, pileup stability




$\bar{\mu} = 15$ vs. $\mu > 20$, $\bar{\mu} \simeq 25$

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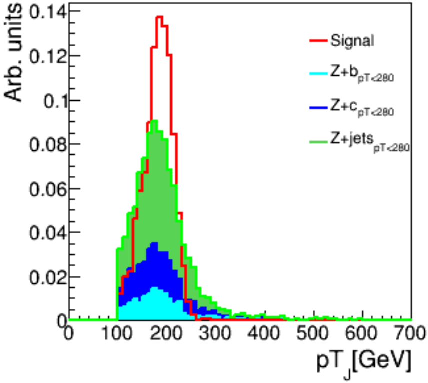
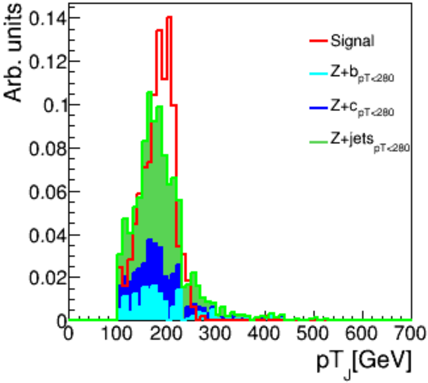
# MC tests: $W'(500\,GeV) \to ZW$, leading fat jet $p_T$

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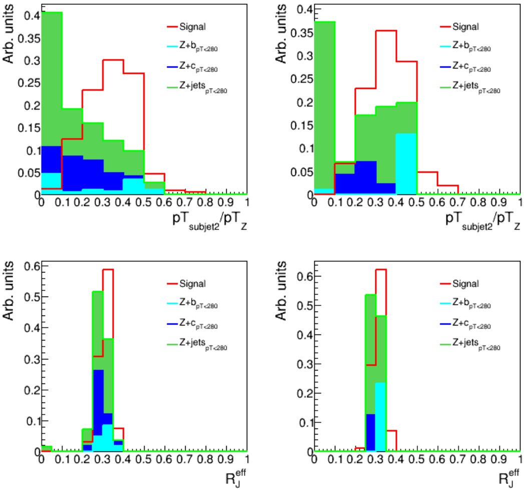
# MC tests: $W'(500\,GeV) \rightarrow ZW$, subjet kinematics vs PU




$\bar{\mu} = 15$ vs. $\mu > 20$, $\bar{\mu} \simeq 25$

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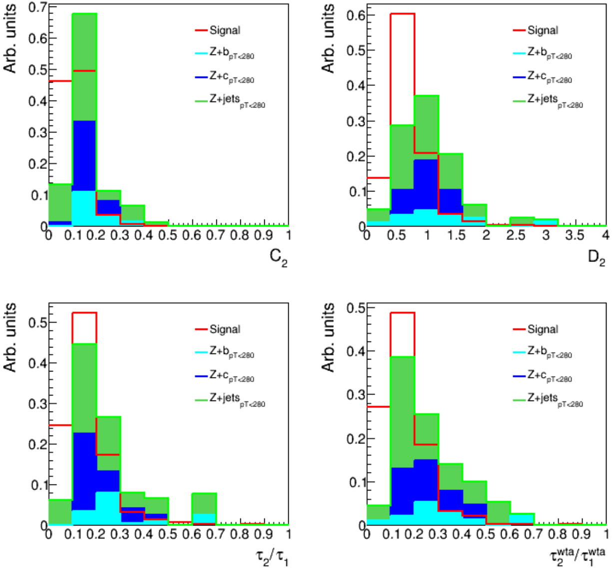
# $W'(500\,GeV) \rightarrow ZW$, $C_2^{(1)}$, $D_2^{(1)}$, $\tau_{21}^{(wta)}$ w/o $p_T^{subjet}/p_T^J$ cut

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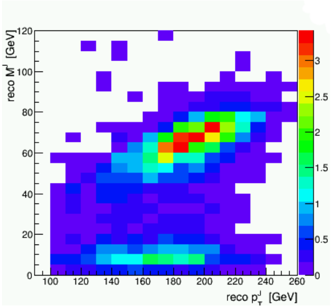
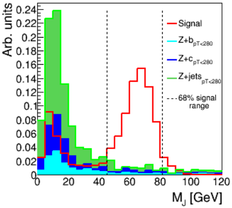
# $W'(500\,GeV) \to ZW$, relaxed fat jet selection

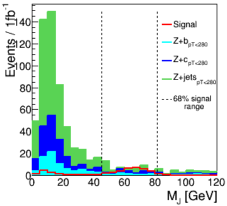
At generator level: $200 < p_T^W < 250$ GeV, no $y_W$ cut.
Relaxed cuts at reco. level: $150 < p_T^J < 300$ GeV, $|y_J| < 4.8$

Poor $p_T^J$ and $m^J$ resolution:

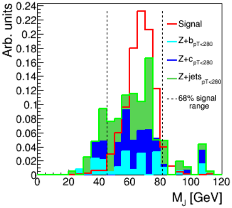


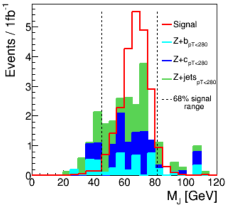

Before structure cuts:

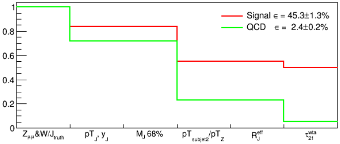



After structure cuts:




Cut flow

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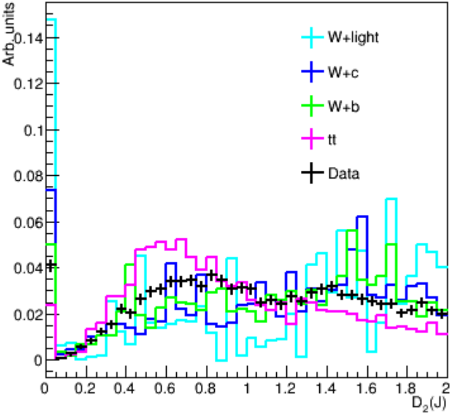
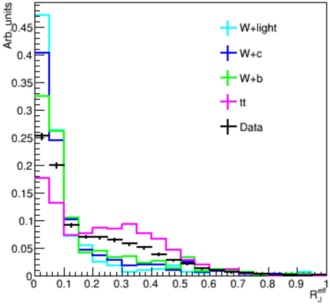
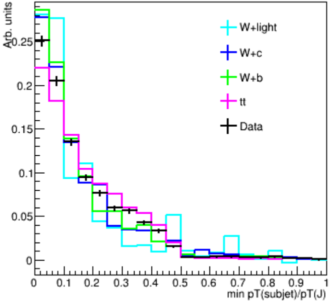
# $t\bar{t}$ 13 TeV data vs MC, structure variables




$\min[p_T^{subjet}/p_T^J]$ can't discriminate between $W \to jj$ and QCD background unlike $W' \to ZW$ case due to mixed $W$ polarization in $t\bar{t}$

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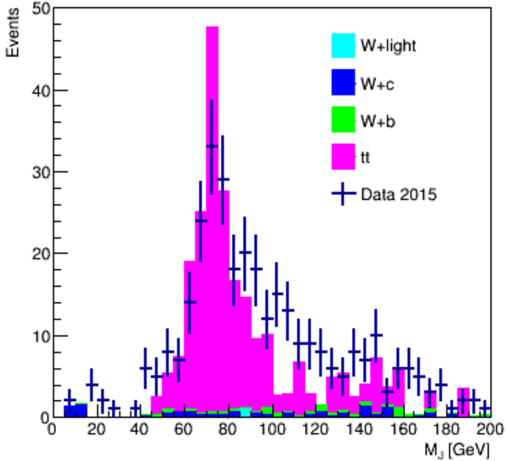
# $t\bar{t}$ 13 TeV, $0.6 < D_2^{(1)} < 1$ and $\Delta R(J, b-jet) > 1$ cuts

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# $D_2$ definition

$$E_{CF0}(\beta) = 1$$

$$E_{CF1}(\beta) = \sum p_{Ti}$$

$$E_{CF2}(\beta) = \sum p_{Ti} p_{Tj} (\Delta R_{ij})^{\beta}$$

$$E_{CF3}(\beta) = \sum p_{Ti} p_{Tj} p_{Tk} (\Delta R_{ij} \Delta R_{ik} \Delta R_{jk})^{\beta}$$

$$e_2^{(\beta)} = E_{CF2}(\beta) / E_{CF1}(\beta)^2$$

$$e_3^{(\beta)} = E_{CF3}(\beta) / E_{CF1}(\beta)^3$$

$$D_2^{(\beta)} = e_3^{(\beta)} / (e_2^{(\beta)})^3$$

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# Reconstructed $t$ mass vs. $m_{W/b}$ ($1 < D_2 < 1.6$ cut applied)