Searches and techniques for boosted resonances (non-diboson) with the ATLAS detector

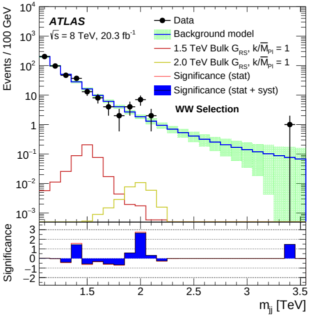
Chris Malena Delitzsch
University of Arizona

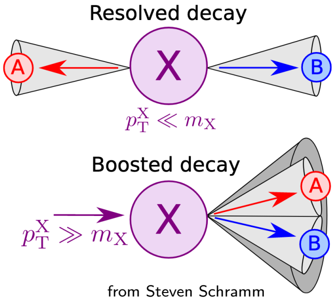
On behalf of the ATLAS Collaboration

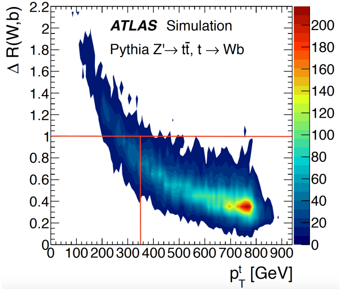
EPS-HEP2021

July 26 - 30, 2021

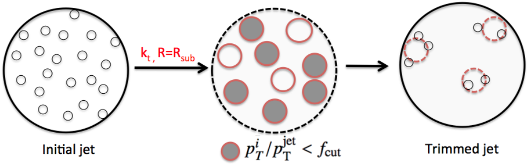
- Many theories for new physics predict the existence of new resonances (e.g. Z', W')
  - Topcolor-assisted-technicolor, two-Higgs-doublet, warped extra dimensions, composite Higgs
  - Focus here on $Z' \to t\bar{t}$ and $W' \to tb$ resonances
- **Search strategy**
  - Hadronic decays have the highest branching ratios!
  - Search for resonant structure in invariant $t\bar{t}$, tb mass distribution
  - Main challenge is the suppression of the dominant QCD background $\to$ develop taggers



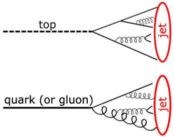


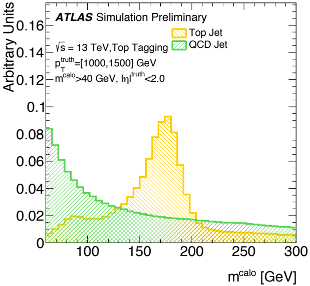


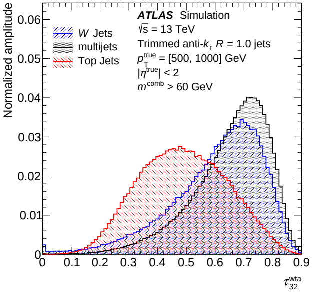
1. **Removal of soft, wide-angle radiation, pile-up effects**
   - Constituent-level pile-up suppression: e.g. Constituent Subtraction, SoftKiller
   - Grooming algorithm: e.g. trimming (Run-2 default up to now), Soft Drop (new default)

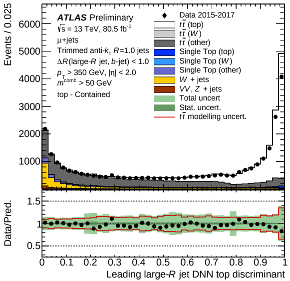


1. **Removal of soft, wide-angle radiation, pile-up effects**
   - Constituent-level pile-up suppression: e.g. Constituent Subtraction, SoftKiller
   - Grooming algorithm: e.g. trimming (Run-2 default up to now), Soft Drop (new default)
2. **Jet substructure variables / taggers**
   - Study the internal structure of the jet to distinguish e.g. top jets from q/g-initiated jets
   - Simple taggers: cut on jet mass + one other substructure variable (e.g. N-subjettiness)
   - Complex taggers: Deep Neural Networks (DNN) trained on various substructure variables
   - Taggers are calibrated in data via scale factors (SF) using $t\bar{t}$, multijet and γ+jet events

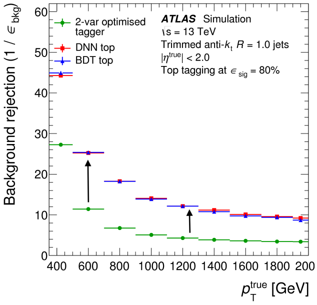


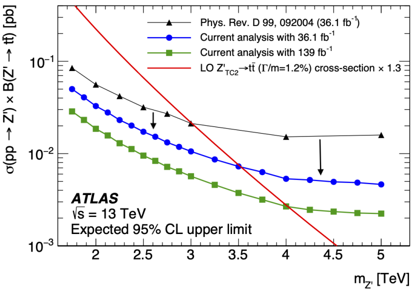


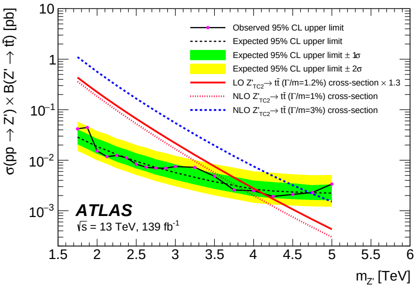




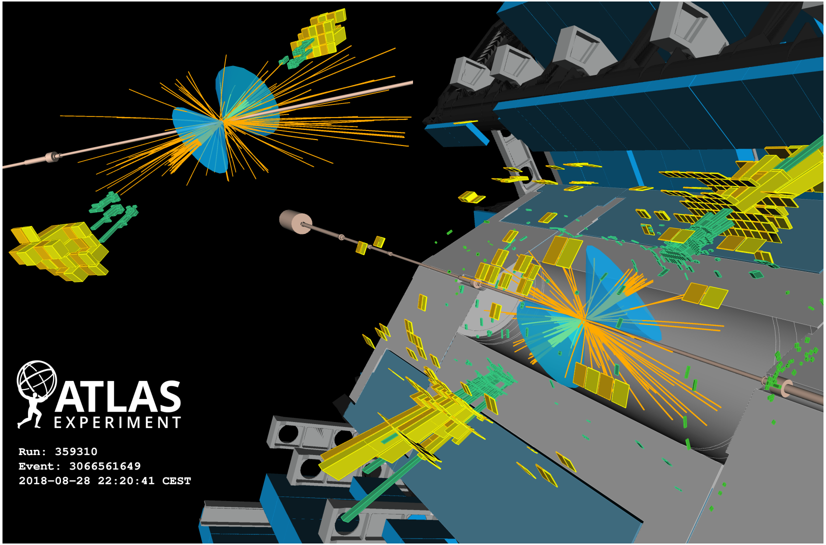
- Search performed using full Run-2 dataset (139 fb^{-1})
- DNN tagger used to identify boosted top quark decays @ 80% signal efficiency + b-tagged variable-R track jet (77% WP)
- Data-driven background estimation using fit function
- Largest systematic uncertainties from tagging SFs (and b-tagging)
    - Dominated by generator differences when calibrating efficiency in MC to data



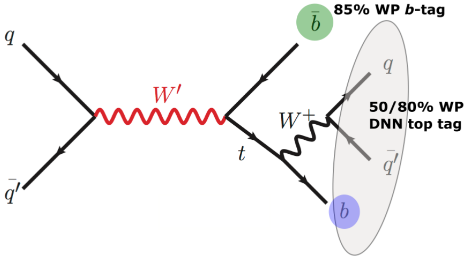




Event Display of $t\bar{t}$ event



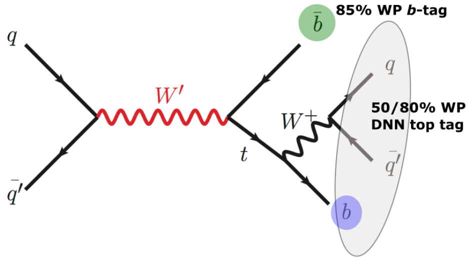
- Search for $W' \to t\bar{b} \to q\bar{q}'b\bar{b}$ using 139 fb^{-1}
- Searches done separately for left- and right-handed gauge bosons
- Here: only results for right-handed W'
- See poster by Kuan-Yu Lin for more details!



Signal regions

- SR1: 50% top tag, 1 b-jet with $\Delta R(\text{top}, b\text{-jet}) < 1.0$ and one add. b-jet
- SR2: 80% but not 50% top tag, 1 b-jet with $\Delta R(\text{top}, b\text{-jet}) < 1.0$, one add. b-jet
- SR3: 50% top tag, 0 b-jet with $\Delta R(\text{top}, b\text{-jet}) < 1.0$ and one add. b-jet

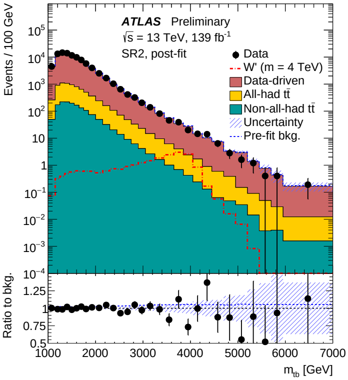
- Discriminating variable: tb invariant mass
- $t\bar{t}$ background taken from simulation
- Data-driven multijet background estimate
- Various regions defined based on top tagging decision and b-jet requirements

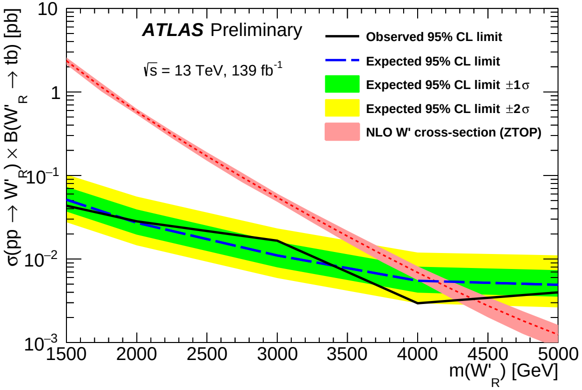


Top tagging	0 small-R b-tags	1 small-R b-tag
50% WP	**B**	**A: Signal Region 1**
80% WP	**D**	**C: Signal Region 2**
Loose tag	**F**	**E**

$$N^{\mathrm{bkg}}_{\mathrm{SR1},\ \mathrm{SR2}}(i) = \left(N^{\mathrm{data}}_{B,D}(i) - N^{t\bar{t}}_{B,D}(i)\right)\frac{N_E(i)}{N_F(i)}$$

- Good agreement is observed between the data and prediction without any significant excess
- Limits set on $\sigma\times$ BR excluding right-handed W' with masses $<$ **4.4 TeV**
- Previous limits on right-handed W':
  - CMS excluded $m_{W'} < 3.4$ TeV (all-had) using 137 fb^{-1}: 2104.04831
  - ATLAS excluded $m_{W'} < 3.25$ TeV (all-had. + lepton+jets) using 36.1 fb^{-1}: 1807.10473.



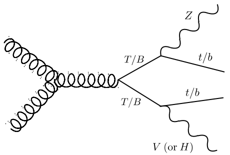


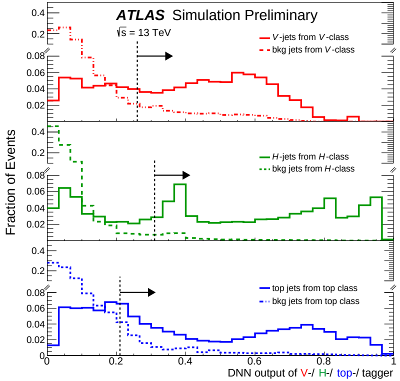
Search for pair-production of vector-like quarks

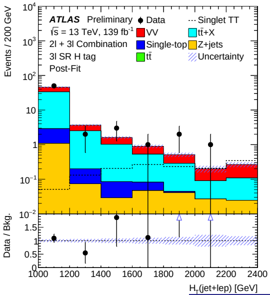
ATLAS-CONF-2021-024

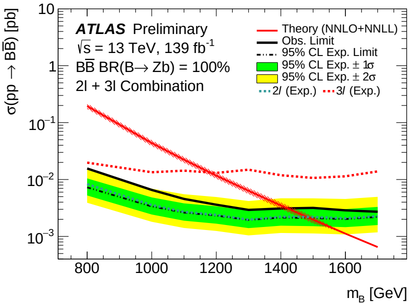
- Large-R reclustered (RC) jets used to identify V/H, top
  - Reclustered jets: small-R jet input to jet clustering
- Multi-Class Boosted Object Tagger (MCBOT)
  - DNN trained with 18 inputs variables to identify jet origin
    - p_{T}, mass, RC constituents (i.e $N_{\mathrm{small}-R}$) + 4-vector, b-tagging score of three leading p_{T} RC constituents
  - Simultaneous identification of V/H/top jets
  - In case of ambiguities, choose tag with highest DNN score

- See also Mesut's talk later

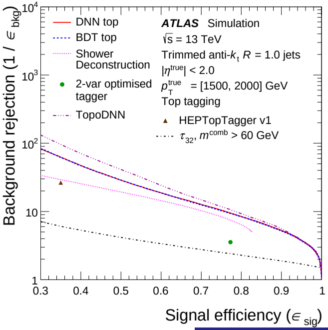


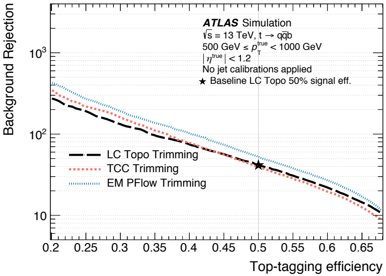


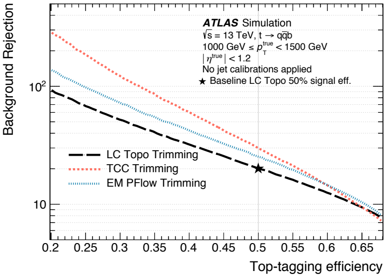




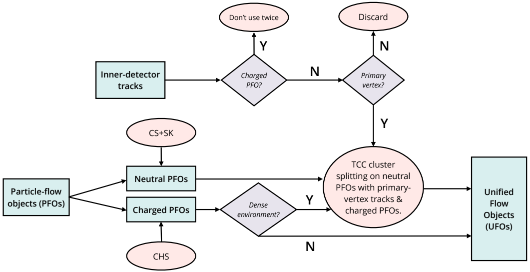
1. Develop more sophisticated taggers, e.g. use jet constituents as input
2. Develop new, more advanced jet definitions
   - Most analyses in ATLAS use large-R jets reconstructed only from calorimeter info
     - At high p_{T}, full decay sometimes reconstructed within one topological cluster
   - Different algorithms used to take advantage of inner detector tracks
     - Particle Flow (PFlow): takes advantage of excellent track p_{T} resolution at low p_{T}
     - Track-CaloClusters (TCC): uses tracks angular information at high p_{T} + cluster splitting

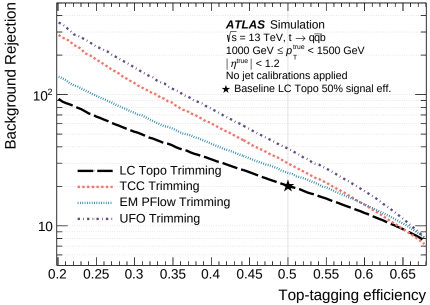


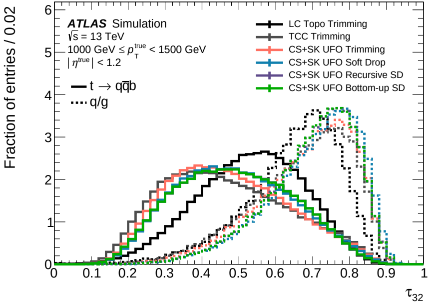




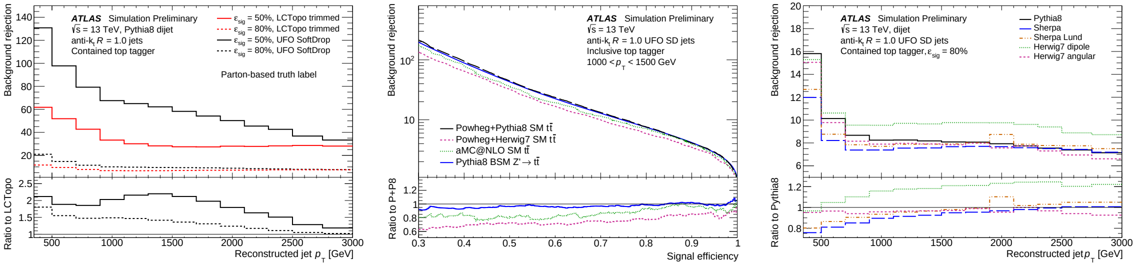
- New input type developed that takes advantage of PFlow and TCC algorithm
- UFOs outperform other inputs over broad range
- ATLAS re-optimised the choice of grooming algorithm using various metrics: tagging perf., mass resolution, pile-up dependence







- DNN top tagger was re-optimised for new UFO jet collection !!!NEW!!!
  - $R = 1.0$ UFO jets (with const. pile-up suppression (CS+SK)) + Soft Drop ($\beta = 1$, $z_{\mathrm{cut}} = 0.1$)
- Input variables: τ_1, τ_2, τ_3, τ_4, $\sqrt{d_{12}}$, $\sqrt{d_{23}}$, ECF_1, ECF_2, ECF_3, C_2, D_2, L_2, L_3, Q_{W}, T_{M}
- Two taggers developed for inclusive tops and contained tops at 50/80% sig. eff.
- Performance compared for new UFO taggers with respect to previous LCTopo taggers
  - When applied to the same signal events, UFO taggers outperform LCTopo taggers
- Generator differences are one of the main uncertainties in the calibration of boosted taggers



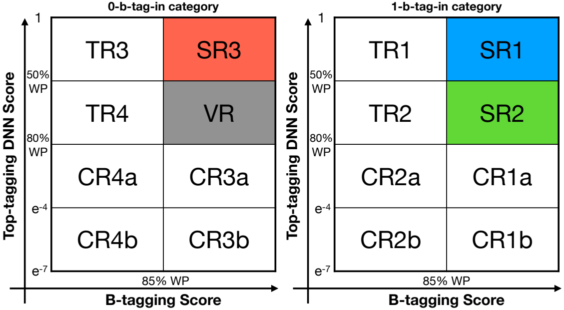
Summary

- Many exciting searches for new physics have been performed
  - Focussed here only on final states involving hadronically-decaying top quarks
  - New impressive limits set on right-handed W' gauge bosons
  - Unfortunately no discover yet but we will keep increasing the sensitivity to smaller signal cross-sections by improving the performance of boosted top/W/Z/H taggers
- Analyses presented here use cutting-edge techniques for boosted top identification
- DNN taggers developed to identify single objects as well as multiclass object tagging
- New inputs developed for jet reconstruction that significantly enhance performancee over broad range

Backup

Data-driven background estimation in $W' \to tb$ search

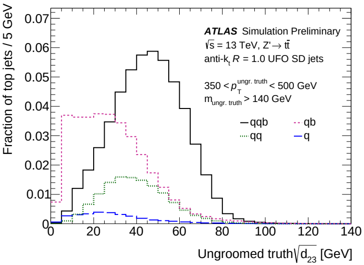
- VR: validation region
- TR: template region
- CR: control region
- SR: signal region

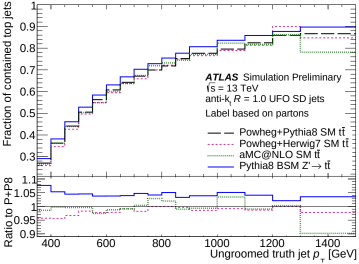


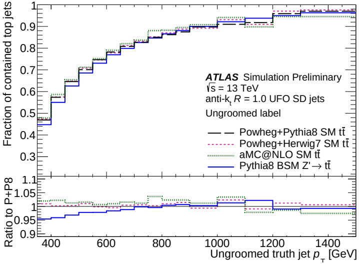
$$N^{\text{data-driven-background}}_{\text{SR1,SR2}}(i) = R^{1}_{\text{corr}}(i) \times (N^{\text{obs}}_{\text{TR1,TR2}}(i) - N^{t\bar{t}}_{\text{TR1,TR2}}(i)) \times \frac{N^{\text{obs}}_{\text{CR1a}}(i)}{N^{\text{obs}}_{\text{CR2a}}(i)}$$

- $R^{1}_{\text{corr}}(i)$: accounts for correlation between top tag and b-tagging
- $N^{t\bar{t}}_{\text{TR1,TR2}}(i)$: subtract tt (taken from MC)
- $N^{\text{obs}}_{\text{CR1a}}(i) / N^{\text{obs}}_{\text{CR2a}}(i)$: scale by yield from 0-tag to 1-tag region

- DNN top tagger was re-optimised for new UFO jet collection !!!NEW!!!
  - anti-k_t $R = 1.0$ jets reconstructed from UFOs with constituent pile-up suppression (CS+SK)
  - Grooming algorithm: Soft Drop with $\beta = 1$ and $z_{\text{cut}} = 0.1$
- Input variables: τ_1, τ_2, τ_3, τ_4, $\sqrt{d_{12}}$, $\sqrt{d_{23}}$, ECF_1, ECF_2, ECF_3, C_2, D_2, L_2, L_3, Q_{W}, T_{M}
- Two taggers developed for inclusive tops and contained tops
  - Contained tops: full top quark decay reconstructed within jets
    - Particle-level information used to define contained jets using mass and splitting scale
    - New labelling reduces generator dependence





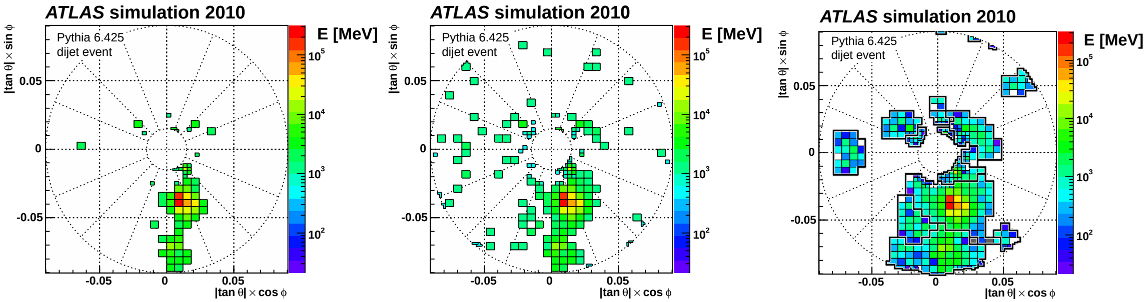


Inputs to jet reconstruction - Topoclusters

- Group of topologically connected cells based on their significance

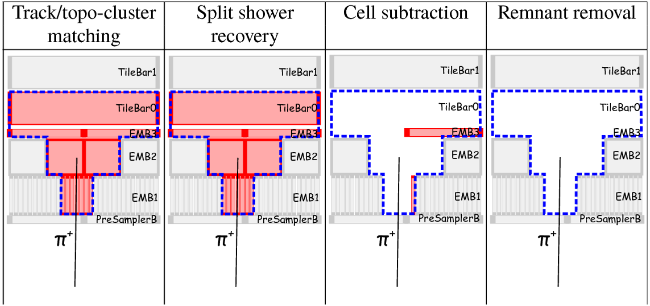
$$\varsigma_{\text{cell}}^{\text{EM}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise, cell}}^{\text{EM}}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sqrt{\left(\sigma_{\text{noise}}^{\text{electronic}}\right)^2 + \left(\sigma_{\text{noise}}^{\text{pile-up}}\right)^2}}$$

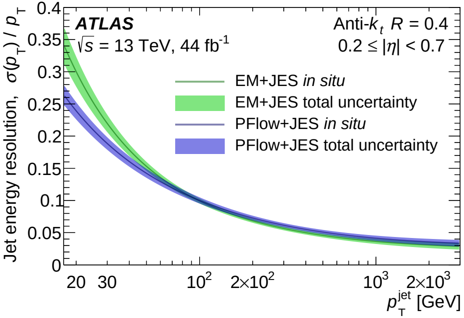
- Limitations: high p_{T} objects can be reconstructed within one topocluster



Inputs to jet reconstruction - Particle Flow

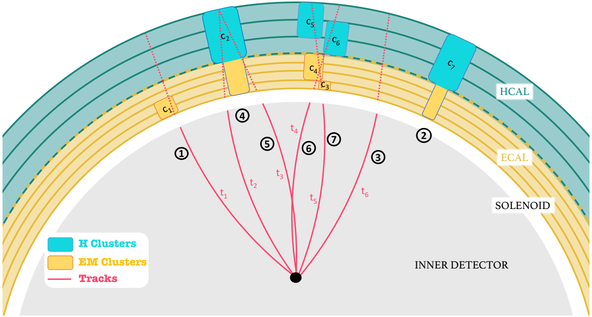
- Benefits from better p_T resolution of tracks at low p_T
- Match tracks to clusters and subtract energy of charged particle cell-by-cell
- We slowly switch off Particle Flow at higher momenta

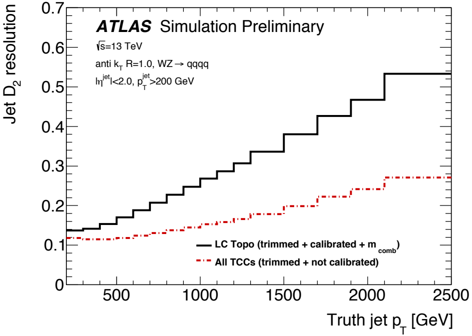




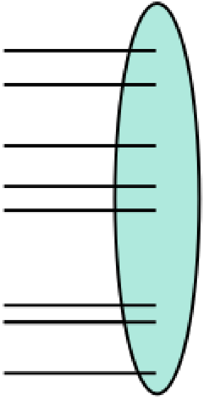
Inputs to jet reconstruction - TCC

- Boosted object can be reconstructed within one cluster at high p_{T}
- Split cluster using tracking information (excellent angular resolution)

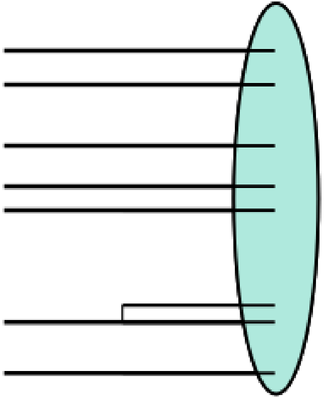




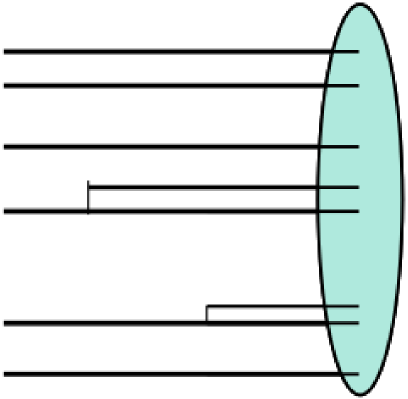
Cambridge-Aachen illustration



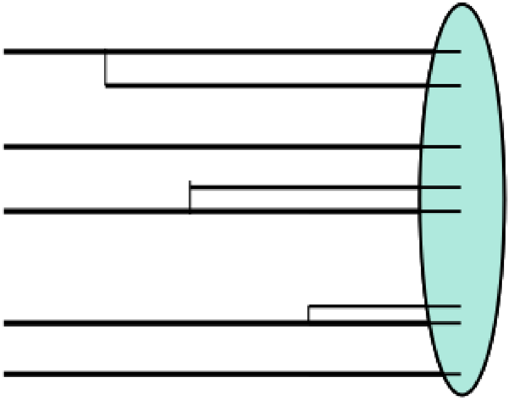
Cambridge-Aachen illustration



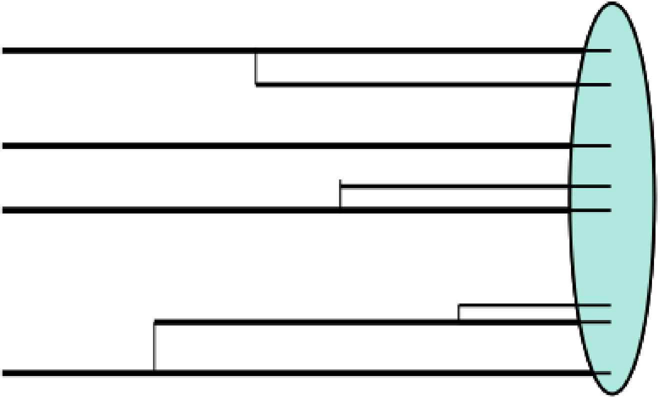
Cambridge-Aachen illustration



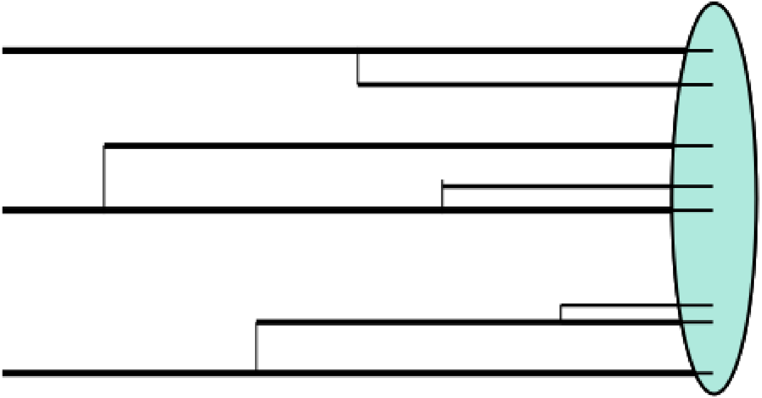
Cambridge-Aachen illustration



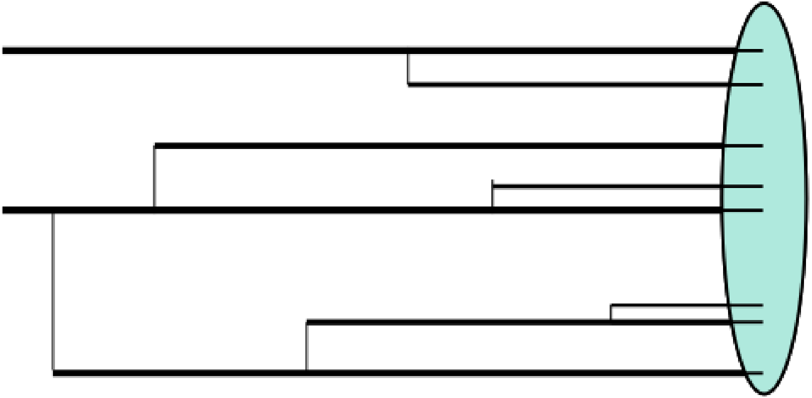
Cambridge-Aachen illustration



Cambridge-Aachen illustration



Cambridge-Aachen illustration



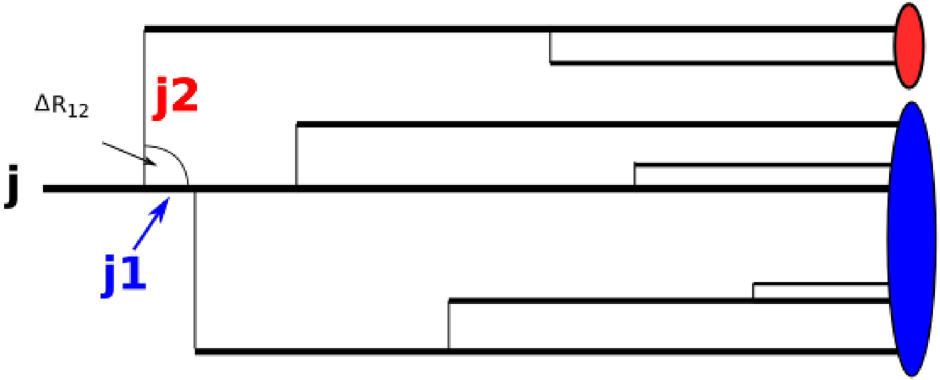
Cambridge-Aachen illustration

Soft Drop algorithm at work

$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

Soft Drop algorithm at work

$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$



Soft Drop algorithm at work

$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

Soft Drop algorithm at work

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

Soft Drop algorithm at work

$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$