Jet structure and event shapes at the LHC

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April 25, 2019

Measuring jet substructure

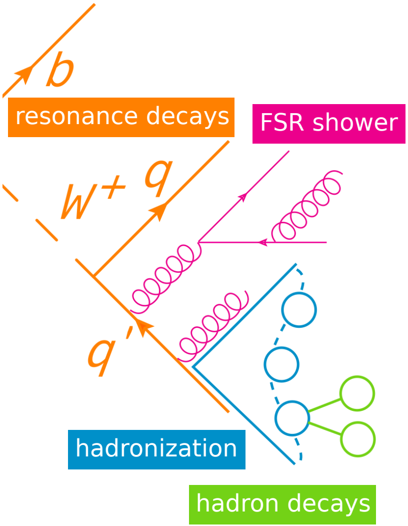
Introduction

- MC in experiments: fragmentation of quarks and gluons to jets described by parton shower + hadronization model
- Current models are tuned to LEP $Z \rightarrow q\bar{q}$ data

Better knowledge of jet substructure

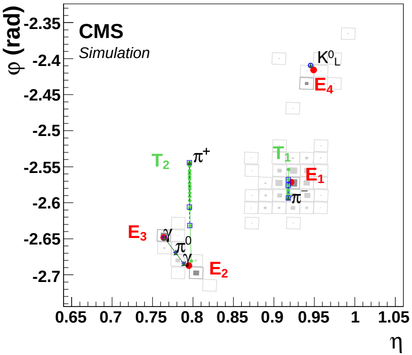
will help to improve...

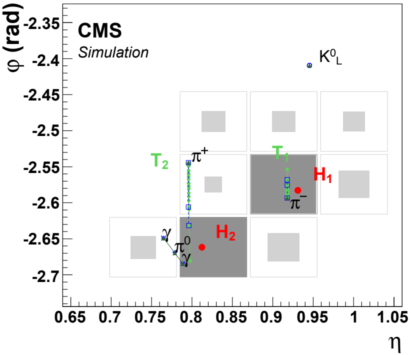
- Precision measurements involving jets (H, top)
- BSM searches with boosted objects
- Flavour tagging, pileup ID

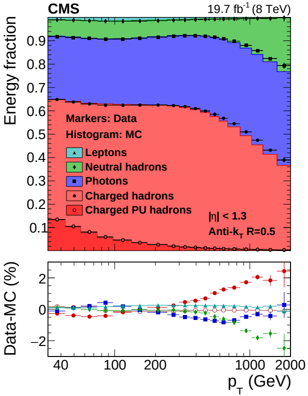


CMS Particle flow reconstruction

CMS PRF-14-001



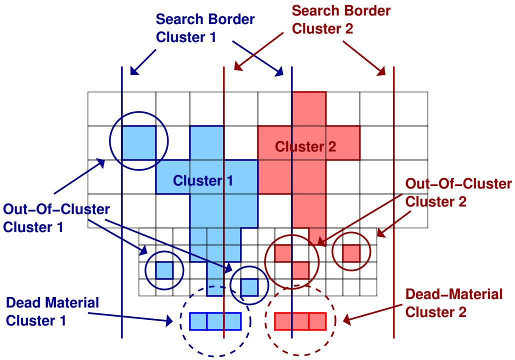


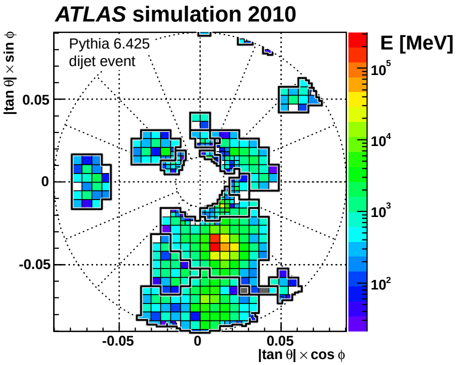


- Excellent tracking (silicon, 4 T magnetic field), most efficient for $1\,\text{GeV} < p_T < 10\,\text{GeV}$
- Electromagnetic crystal calorimeter with excellent E resolution, $\Delta\eta \times \Delta\phi = 0.017 \times 0.017$
- Hermetic brass-scintillator hadronic calorimeter (0.087×0.087)
- PF algorithm keeps all tracks, and removes their energy from calorimeter towers
- Charged hadron subtraction (CHS) removes tracks not from primary vertex
- PUPPI algorithm weighs down neutral clusters not close to PV tracks arXiv:1407.6013

ATLAS Topological cell clustering

ATLAS PERF-2015-09





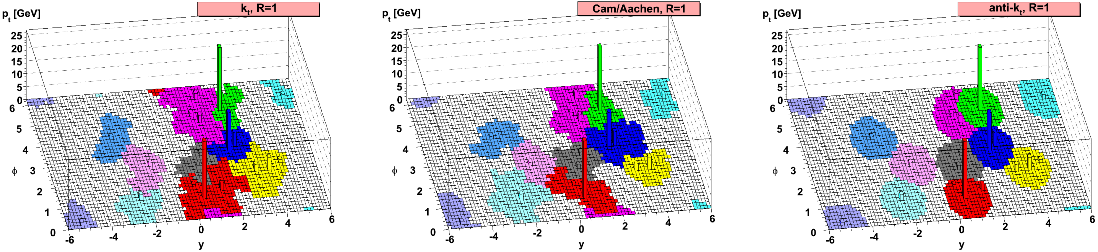
- Liquid argon ECAL (0.025×0.025), steel-scintillator HCAL (0.1×0.1), both with longitudinal segmentation and good energy resolution but more dead material (magnet)
- 3D topological clustering of calorimeter, starting from cells with high signal significance
- Tracking (silicon, 2T field) mainly used for b/c/τ tagging and cluster calibration
  - PF algorithm developed but not in regular use yet ATLAS PERF-2014-07
  - Several algorithms for track-assisted jet reconstruction ATLAS PHYS-PUB-2018-012

Jet reconstruction

arXiv:0802.1189

- Sequential cluster algorithms defined by the two quantities

$$d_{ij} = \min\left(p_{T,i}^{2k}, p_{T,j}^{2k}\right)\frac{\Delta_{ij}^2}{R^2},\ d_{iB} = p_{T,i}^{2k}$$



- Behavior controlled by parameter $k = \begin{cases} 1 & \text{Durham } k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti} - k_t \end{cases}$

  $\rightarrow$ different sensitivity to soft particles (soft emissions, pileup, underlying event)

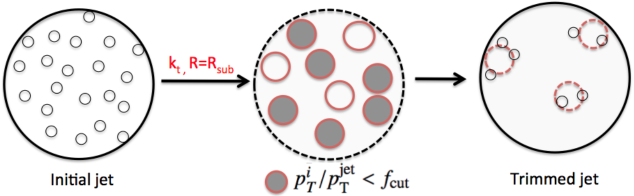
Grooming methods

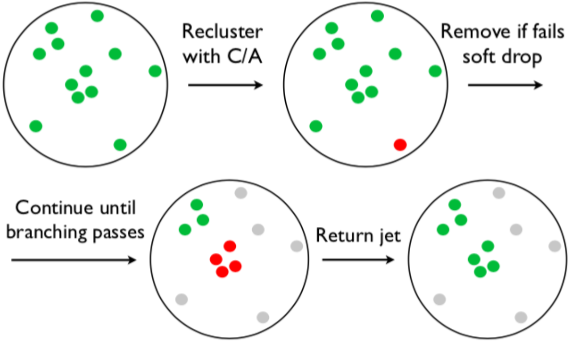
Modify jets to reduce impact of soft radiation and pileup events.
Various methods, for example:

- **Trimming** arXiv:0912.1342
  Cluster subjets with small R (0.2), remove if below cut (0.05)

- **Soft drop** arXiv:1402.2657
  C/A declustering, stop if
  $$\frac{\min\left(p_T^{j1}, p_T^{j2}\right)}{p_T^{j1} + p_T^{j2}} > z_{cut} \left(\Delta R_{12}/R\right)^{\beta}$$

Figures from ATLAS PERF-2012-02 and A. Larkoski (LPC 2014)

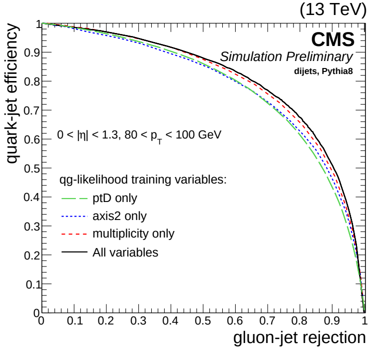


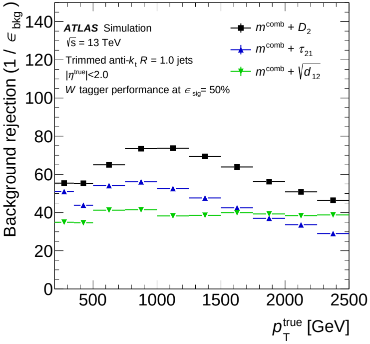


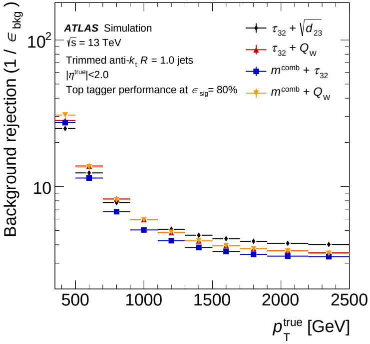
Jet substructure as a tool

ATLAS JETM-2018-03 CMS PAS JME-16-003

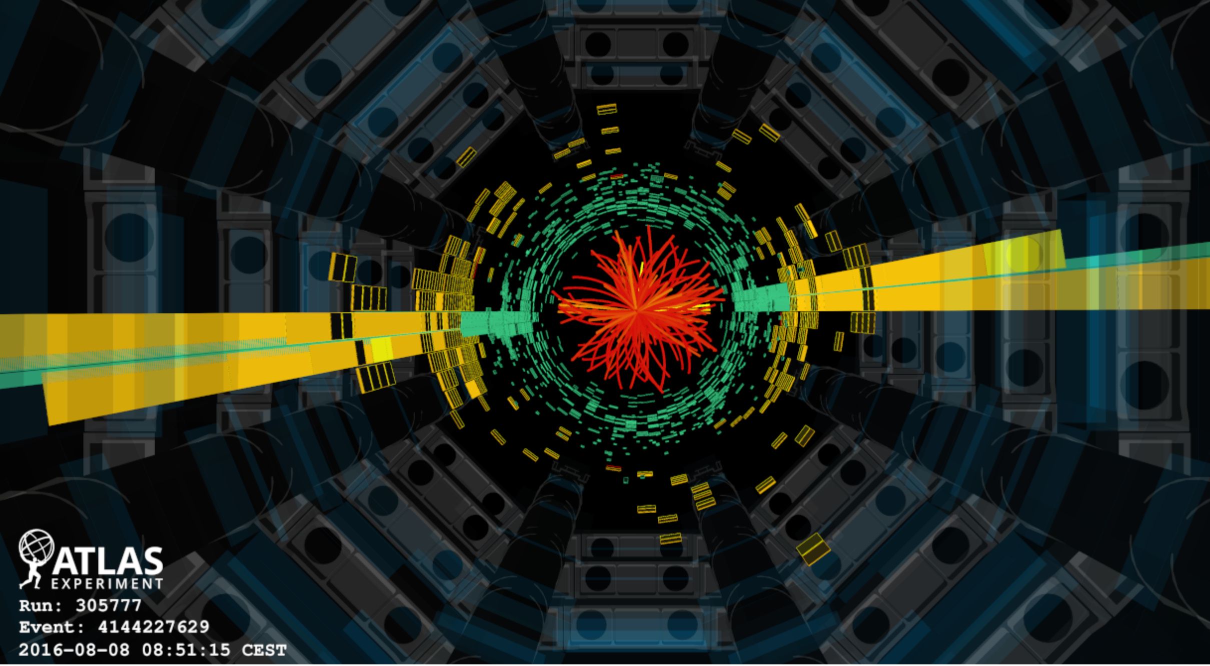
- Quark-gluon tagging, boosted W, boosted tops, used for enhancing precision measurements and searches for new physics
- All taggers based on jet substructure observables
  – or moving to DNNs with tracks/clusters as direct input
  $\rightarrow$ substructure needs to be understood very well to reduce modeling uncertainties



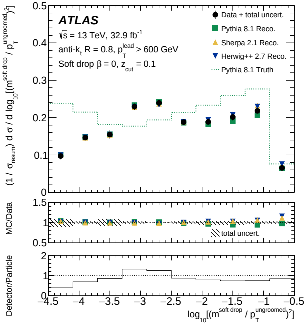


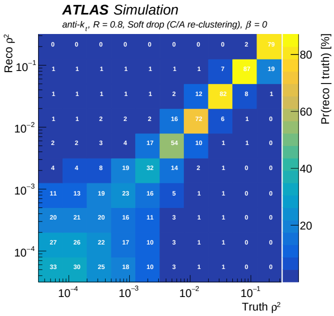


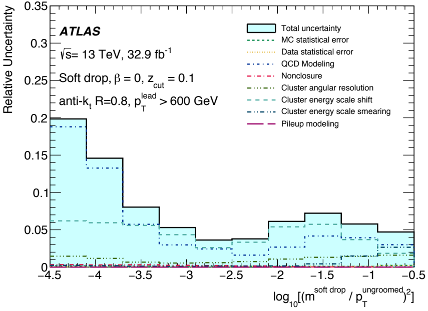
Substructure in dijet events



- Jet mass is simplest observable that requires a calculation at >LO
- Apply soft drop algorithm to remove impact of soft emissions, underlying event, pileup





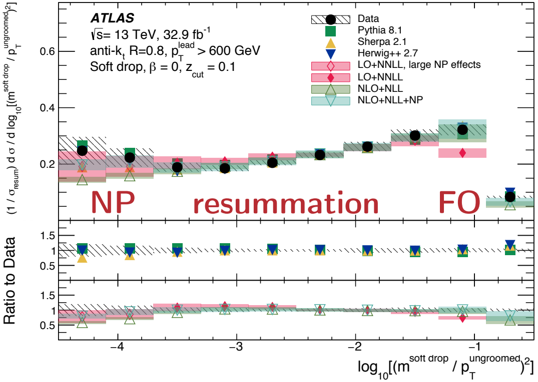


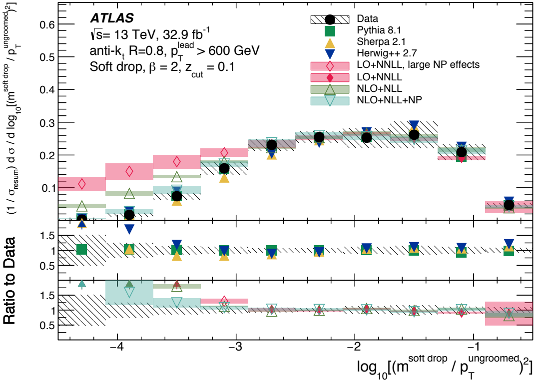
- Measure $\rho = m^{\text{soft drop}}/p_T^{\text{ungroomed}}$ down to $m^{\text{soft drop}} \sim 5\,\text{GeV}$ in bins of $p_T = \{600, 650, 700, 750, 800, 850, 900, 950, 1000, \infty\}$
- Main uncertainties:
  - Cluster energy scale calibration from matched tracks (bottom-up)
  - QCD modeling: exchange unfolding matrix from Pythia to Sherpa ($\neq$ difference between generator predictions!)

Measurement of the soft-drop jet mass

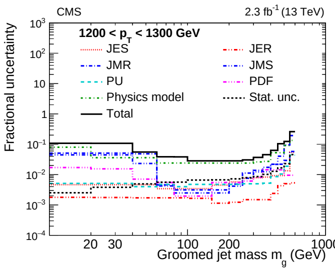
- Data well described by MC and calculations in resummation region
- Large non-perturbative effects significant for $\beta = 2$

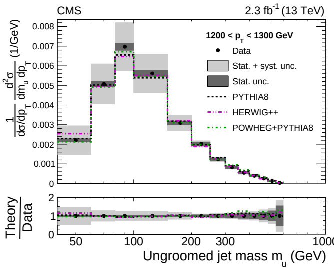
  (SD: stop if $\frac{\min(p_T^{j1}, p_T^{j2})}{p_T^{j1} + p_T^{j2}} > z_{\text{cut}} \, (\Delta R_{12}/R)^{\beta}$)

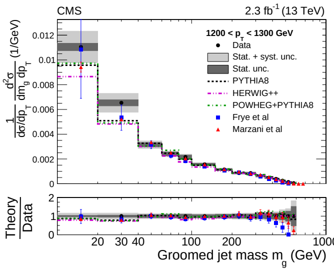




- Measure both ungroomed (m_u) and SD groomed (m_g) jet mass in bins of jet p_T
- Jets clustered from PF+CHS candidates = mostly tracks and "PF photons"
- Main uncertainties:
  - Jet mass scale+resolution calibrated to boosted W bosons (top-down)
  - Physics modeling (Pythia8 vs. Herwig++)





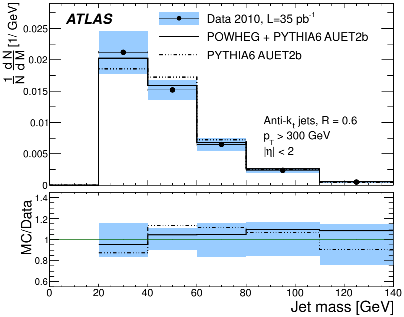


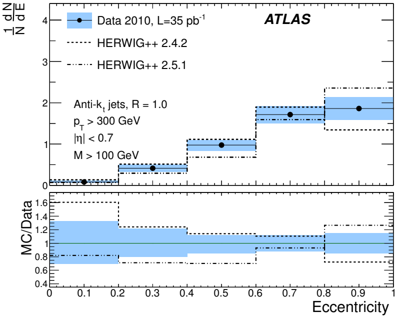
- Grooming lowers the jet mass and reduces the Sudakov peak.
  Improves measurement precision by removing contamination from soft particles and pileup

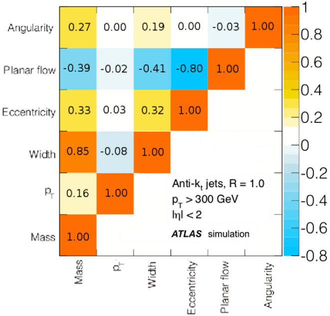
ATLAS Properties of jets at 7 TeV

ATLAS STDM-2011-38 RIVET

- 2010 dataset with very low pileup, measured 5 substructure observables
- Evaluated observable correlations → need to be kept in mind when tuning





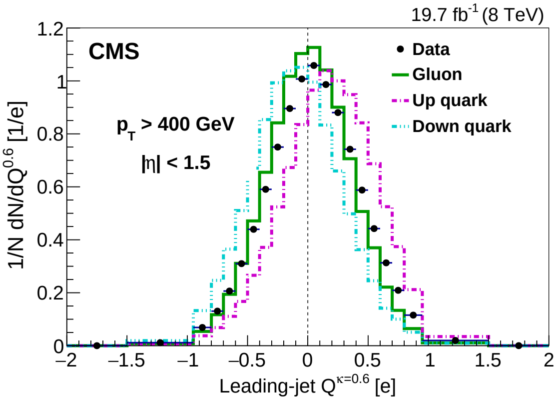


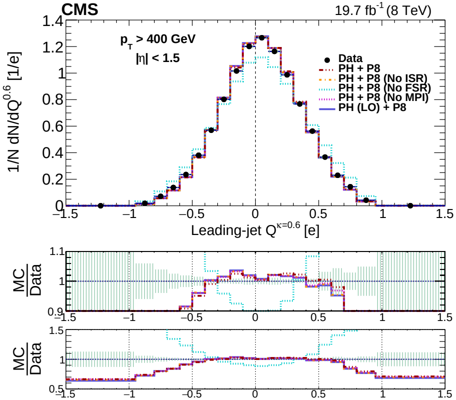
- Jet mass, k_t splitting scales, N-subjettiness on same dataset ATLAS STDM-2011-19

CMS Measurement of the jet charge

CMS SMP-15-003 RIVET

- Jet charge $Q^\kappa = \frac{1}{\left(p_T^{jet}\right)^\kappa} \sum_{i\in PF} Q_i \left(p_T^i\right)^\kappa$, use $\kappa = \{0.3, 0.6, 1.0\}$, as well as $Q^\kappa_{L,T}$
- Differences between up/down quarks and gluons still visible after reconstruction

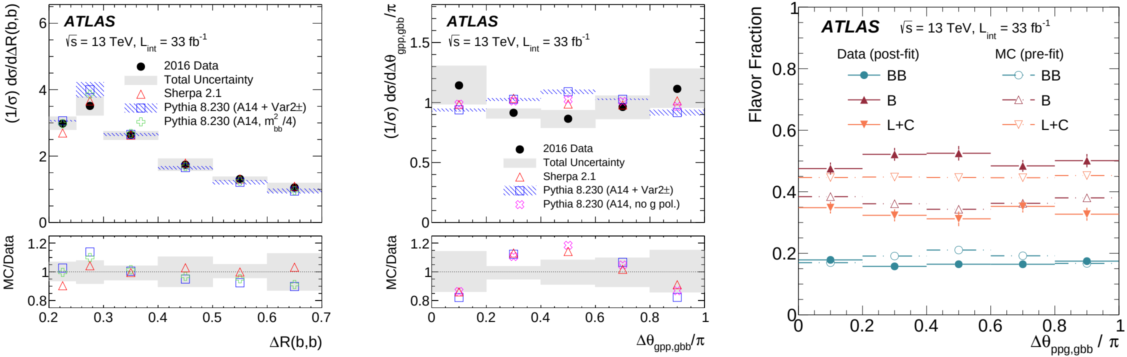




- Leading uncertainties from track p_T resolution and physics modeling
- Result is sensitive to quark and gluon content, and to FSR

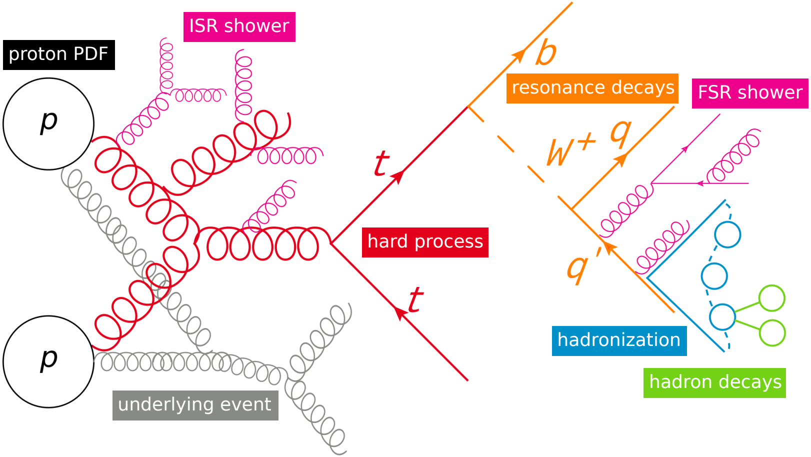
Gluon splitting to $b\bar{b}$

- Probe massive QCD splitting at small angles, main background for $H \to b\bar{b}$
- Large-R (1.0) calo jets with $p_T > 450$ GeV, ≥ 2 small-R (0.2) track jets, ≥ 1 b tag
- Signal fraction $\sim 20\%$, remove non-bb by fit to track impact parameter significance
- Measure $\Delta R\,(b,b)$, $z = p_{T,2}/\left(p_{T,1} + p_{T,2}\right)$, $\Delta\theta_{ppg,gbb}$, $\log\left(m_{bb}/p_T\right)$



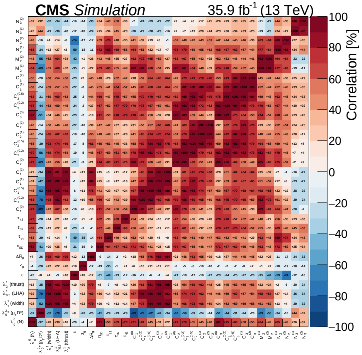
- Significant deviations between data and MC predictions, not covered by FSR variations

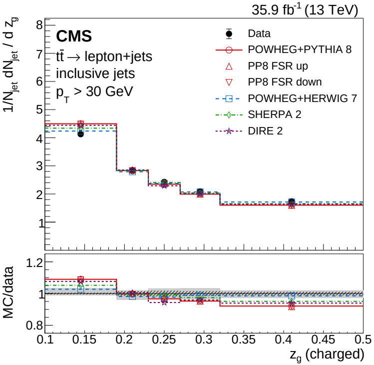
Jet substructure in $t\bar{t}$ production

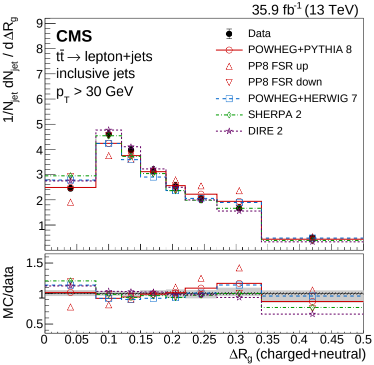


- Very rich final state: high-p_T gluons, light quarks, b quarks, boosted W, boosted top
  $\rightarrow$ standard candle for investigating jet flavors and boosted objects
- Produced abundantly at the LHC!

- Probing jet evolution with angularities, soft drop, energy correlations... $\rightarrow$ 33 observables
- Narrow jets ($\Delta R = 0.4$), unfolded for charged and charged+neutral particles
- Inclusive, bottom, light-enriched (matched to W candidate) and gluon-enriched jet samples $\rightarrow$ 264 distributions but high correlations





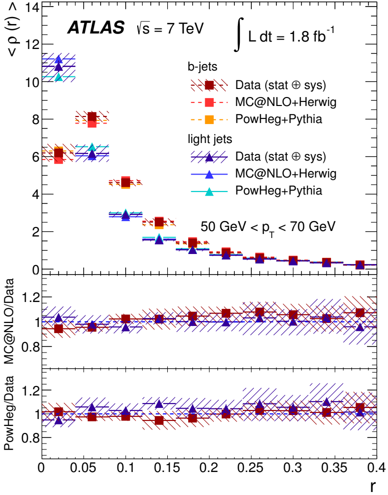


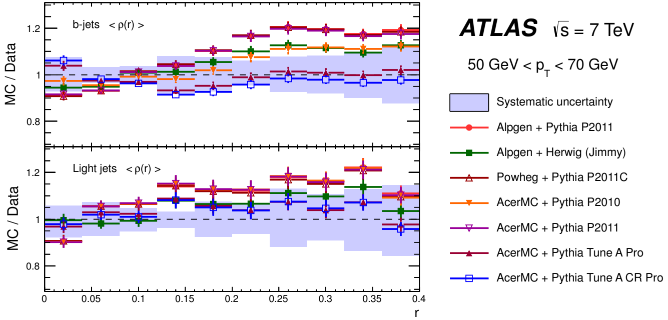
- Preliminary version $\rightarrow$ inclusion of missing $b \rightarrow bg$ splitting functions in Dire NLO shower
- Extract $\alpha_S = 0.115 \pm 0.001\ (\text{exp})^{+0.006}_{-0.003}\ (\text{model})^{+0.014}_{-0.012}\ (\text{scale})$... $t \rightarrow bW + g$ @NLO?

Measurement of jet shapes in $t\bar{t}$ events

ATLAS STDM-2011-48 RIVET

- Measure shape of narrow jets in different jet p_T bins
- Match light jets to W boson $\rightarrow$ 66% purity, energy distribution narrower than for b jets



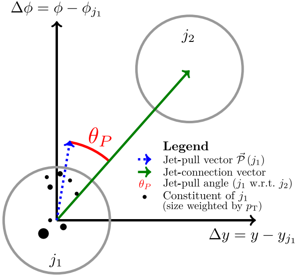


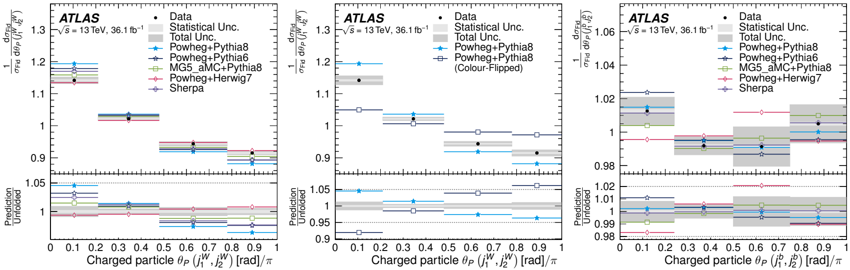
- Also sensitive to UE tunes, probably due to implicit FSR settings

ATLAS Colour flow in $t\bar{t}$ events

ATLAS TOPQ-2017-13

- Measurement of colour flow using jet-pull observable at 13 TeV
- Light jets from W boson are colour-connected
  - Clear peak at low angles, best described by Herwig 7
  - Colour-flipped toy model has flattened distribution
- Pull angle between b jets consistent with random directions, no color connection



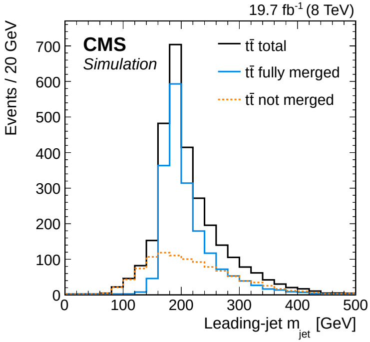


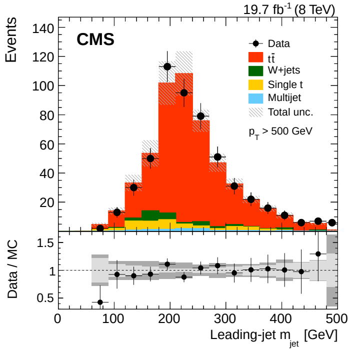
- RIVET available for 8 TeV version ATLAS TOPQ-2014-09

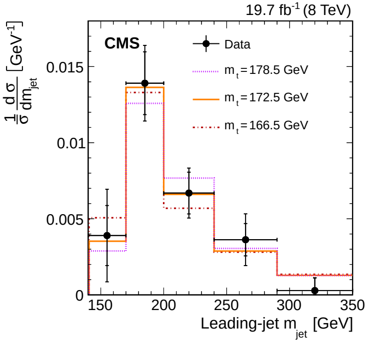
CMS Jet mass in highly boosted $t\bar{t}$ events

CMS TOP-15-015 RIVET

- Select $t\bar{t}$ events with C/A jet ($\Delta R = 1.2$ and $p_T > 400\,\text{GeV}$) as hadronic top candidate



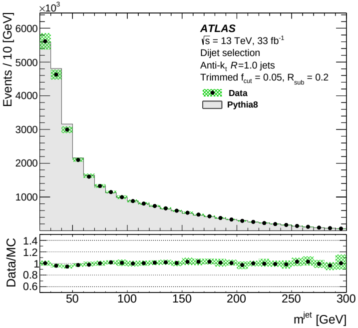


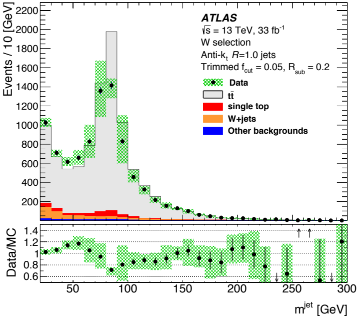


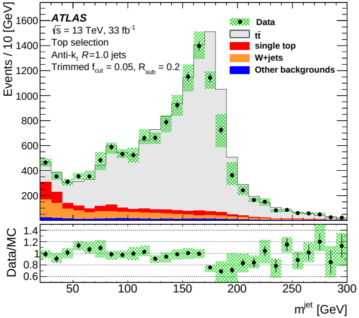
- Measurement limited by statistical precision at 8 TeV
- Potentially sensitive to well-defined top-quark mass, see Hoang et al. arXiv:1803.02321

ATLAS Jet substructure in large–R jets

- Using dijet and $t\bar{t}$ events with trimmed high-p_T anti-k_t jets ($R = 1.0$)
- Leading jet in dijet events: $p_T > 450$ GeV
- Boosted W: $p_T > 200$ GeV, $60 < m < 100$ GeV, b jet within $1.0 < \Delta R < 1.8$
- Boosted top: $p_T > 350$ GeV, $m > 140$ GeV, b jet within $\Delta R < 1.0$

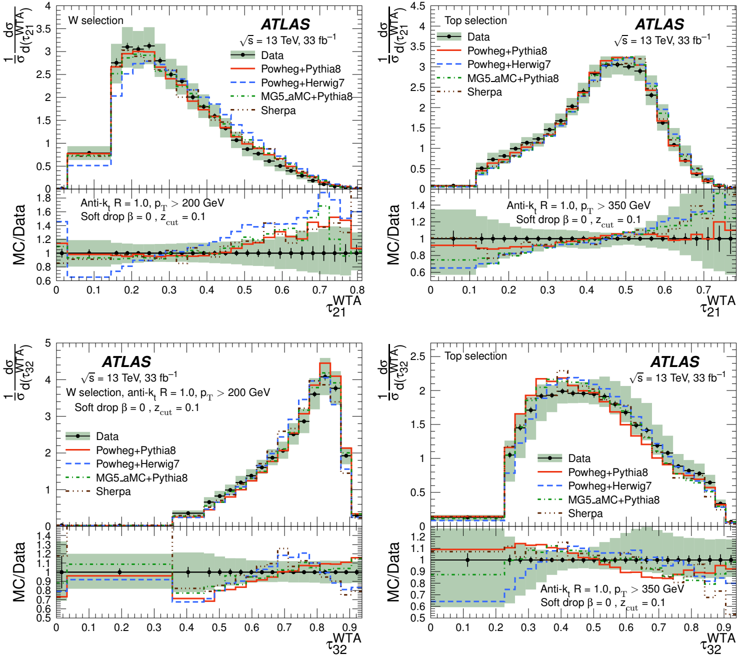






ATLAS Jet substructure in large–R jets

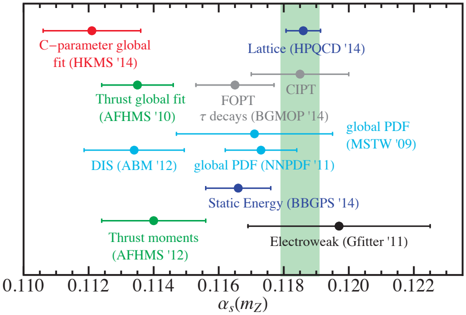
- Revert trimming, apply soft drop grooming
- Unfold number of subjets, LHA, energy correlation functions, N-subjettiness →
- In general good description of data by various MC but uncertainties still large
- W decay: Herwig7 not as 2-prong-like as data? But: no shower variations!

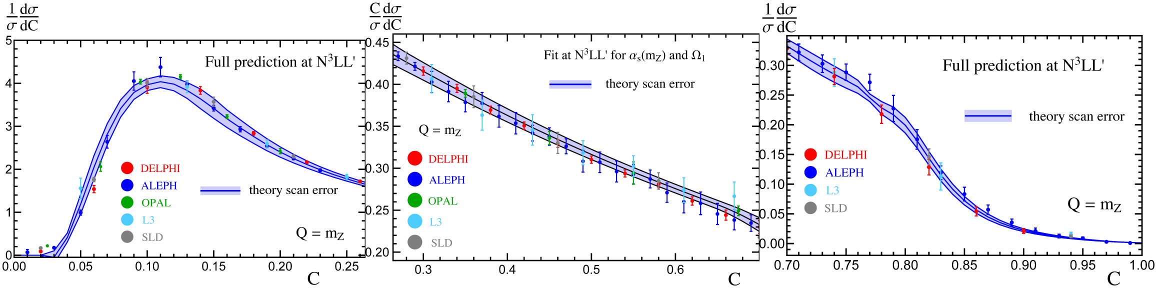


Event shapes

- Many event shapes measured at LEP
- Thrust, C-parameter $\rightarrow$ 0 for dijet events
- Excellent tool for measuring strong coupling
- At LHC:
  - initial state not precisely known
  - more activity in uncovered forward regions

$\rightarrow$ observables redefined in transverse plane



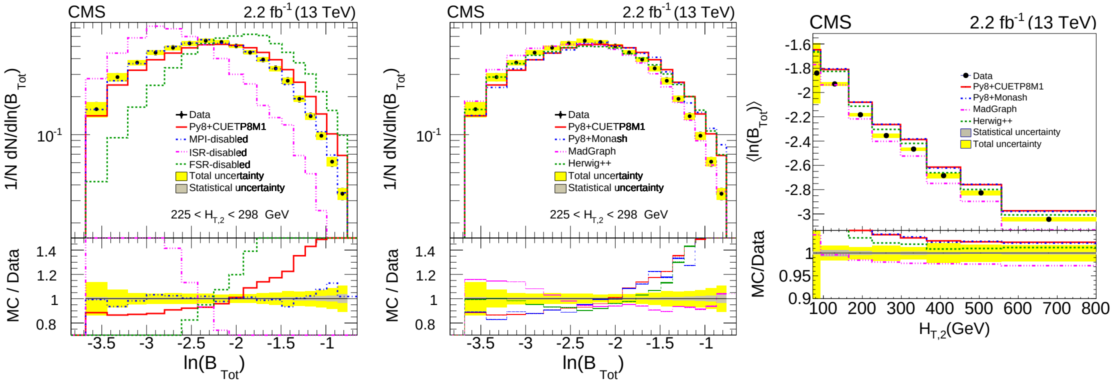


Hoang et al. arXiv:1501.04111

CMS Event shapes in multijet events

CMS SMP-17-003

- Event shape variables defined from 3 jets: leading, subleading, maximizing recoil
- Observables: transverse thrust, total jet broadening, total (transverse) jet mass
- $B_{tot} \equiv B_U + B_L$ with $B_X \equiv \frac{1}{2P_T} \sum_{i \in \mathcal{C}_X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$
  $\rightarrow$ very sensitive to modeling of ISR, FSR, and MPI in jet events

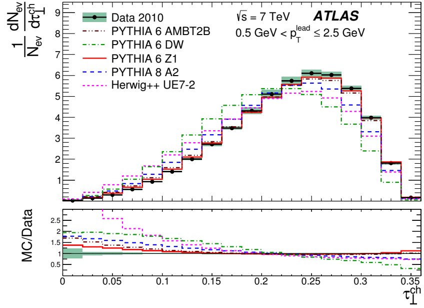


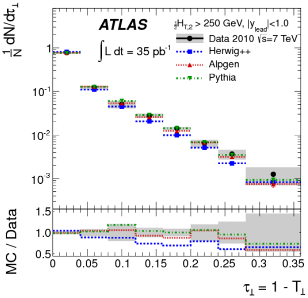
- RIVET available for 7 TeV version CMS SMP-12-022

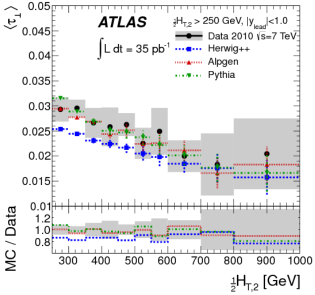
ATLAS Event shape measurements

ATLAS STDM-2011-32 ATLAS STDM-2011-33

- Left: event shapes measured in minimum bias, defined from charged particles RIVET
- Center/right: event shapes measured in multi-jet events, defined from jets
- Complement transverse thrust $\tau_\perp = 1 - T_\perp$, $T_\perp = \max_{\hat{n}} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}|}{\sum_i |\vec{p}_{T,i}|} \to 0$ for dijet



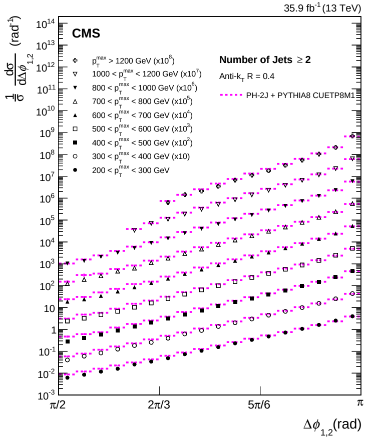


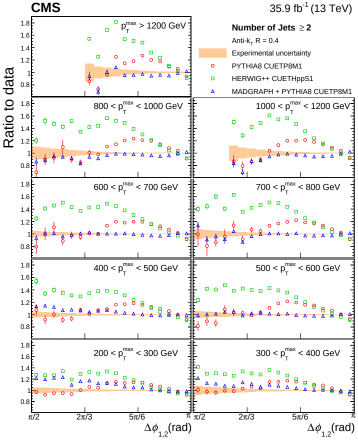


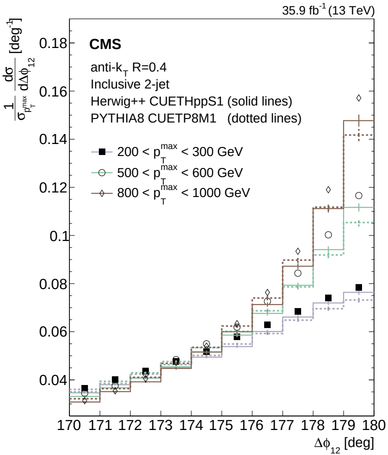
CMS Azimuthal correlations

CMS SMP-16-014 CMS SMP-17-009

- Measure $\Delta\phi_{12}$ = azimuthal separation of two leading jets with $p_T > 100$ GeV
- Large deviations from $\Delta\phi_{12} = 180^\circ$ → need higher-order ME calculations
- Small deviations from $\Delta\phi_{12} = 180^\circ$ → resummation region

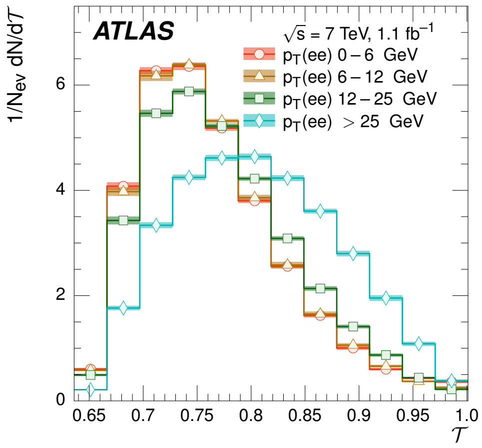


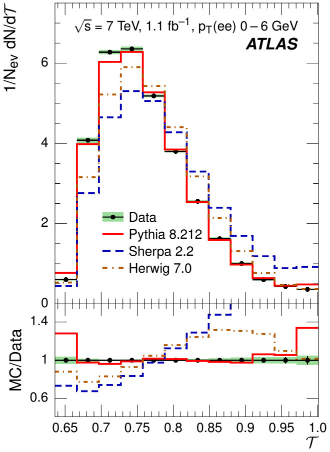


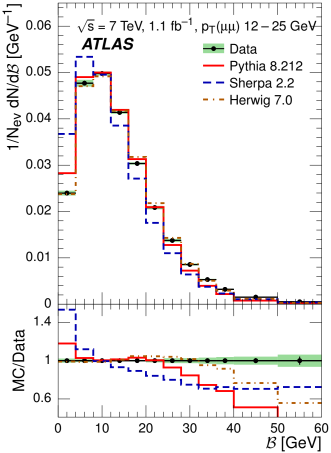


ATLAS Event shapes in Z events

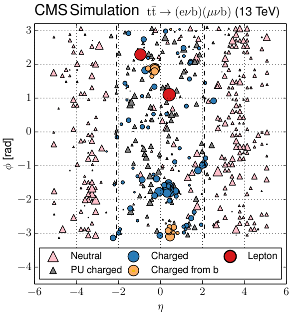
- Select $Z \to \ell^+\ell^-$ events
- Calculate event shapes from charged particles: charged multiplicity, scalar p_T sum, beam thrust, transverse thrust, spherocity, F-parameter
- Beam thrust $\mathcal{B} = \sum_i p_{T,i} \cdot e^{-|\eta_i|}$ (more like summed p_T than thrust)

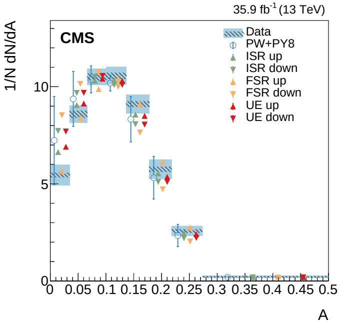


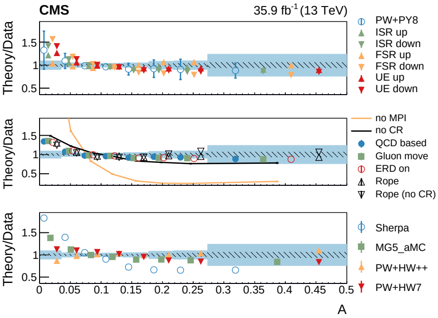




- Probe the underlying event in high-scale process → measured in $t\bar{t}$ dilepton events: charged multiplicity, summed/average momenta; event shapes: sphericity/aplanarity/C/D







- Sensitivity to ISR/FSR variations, shapes prefer more radiation, flux observables less
- Data compared to large range of models: CR models, rope hadronization, Sherpa, Herwig

Summary

- Two main reconstruction strategies:
  - CMS particle flow = tracks + calorimeter
  - ATLAS mostly topological calorimeter clusters
- Jet substructure
  - Used for quark/gluon, boosted W, boosted top tagging
  - Jet mass and other substructure measured in dijet events, latest with soft drop
  - $t\bar{t}$ events give access to samples enriched in jet flavors
- Event shapes in pp collisions sensitive to hard and soft QCD effects
  - Potential for tuning but need ME+PS predictions
- All crucial for validation and further development of QCD modeling!