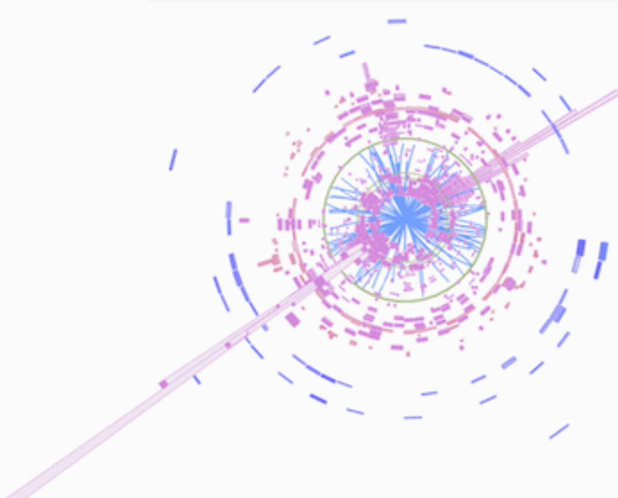
ATLAS EXPERIMENT

Run: 279685
Event: 690925592
2015-09-18 02:47:06 CEST

Jet Reconstruction and Calibration at ATLAS

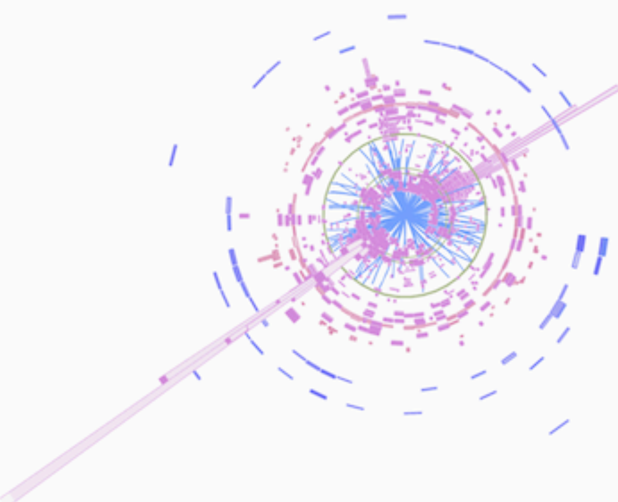


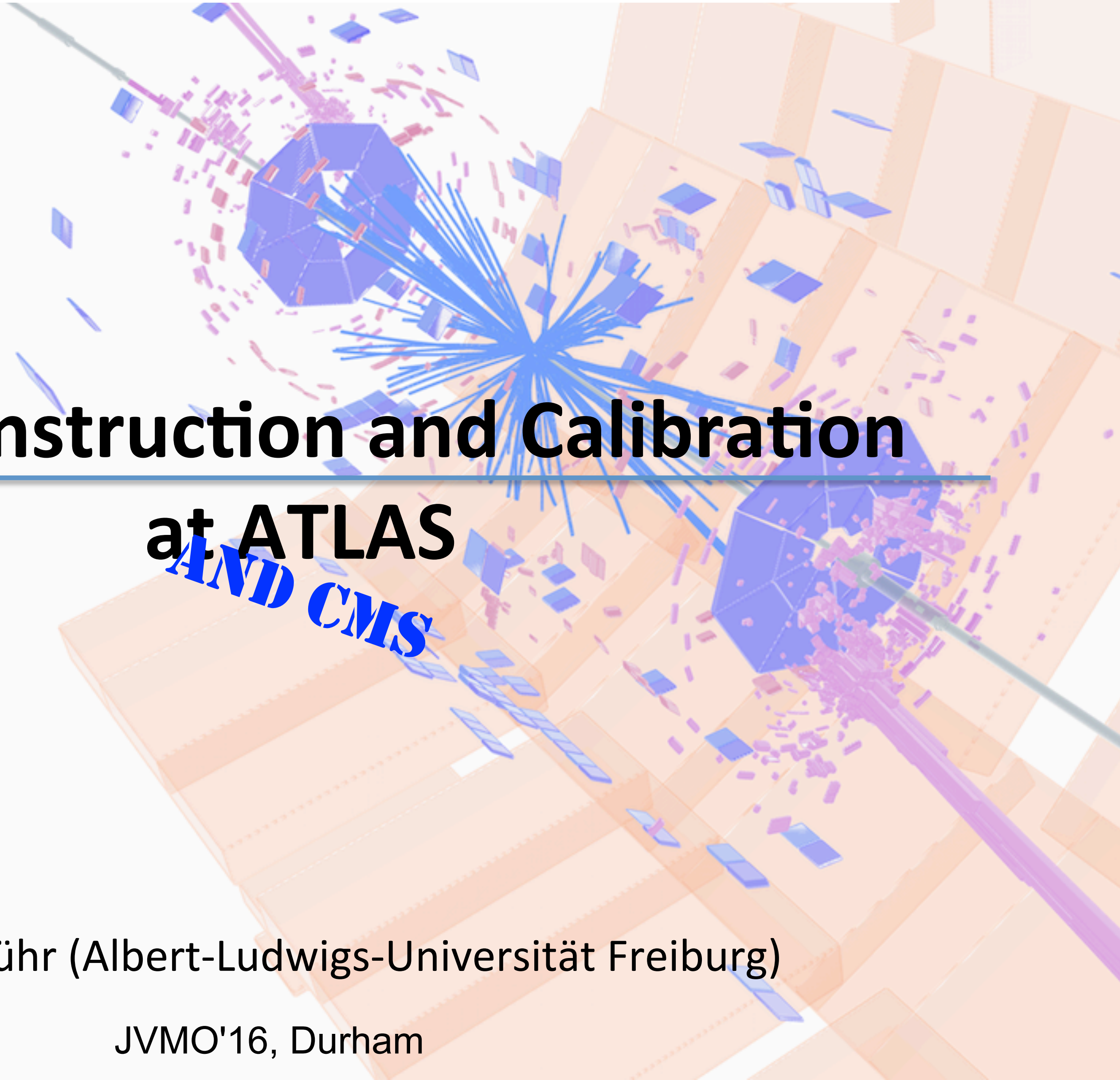
Frederik Rühr (Albert-Ludwigs-Universität Freiburg)

JVMO'16, Durham

Jet Reconstruction and Calibration at ATLAS

AND CMS





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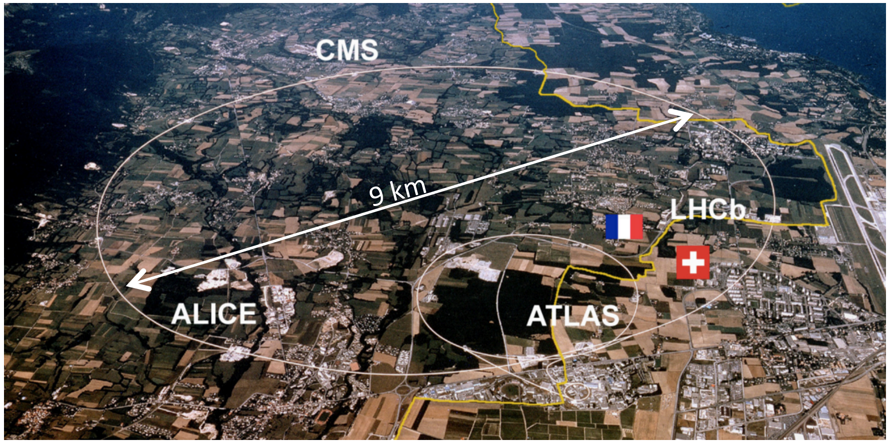
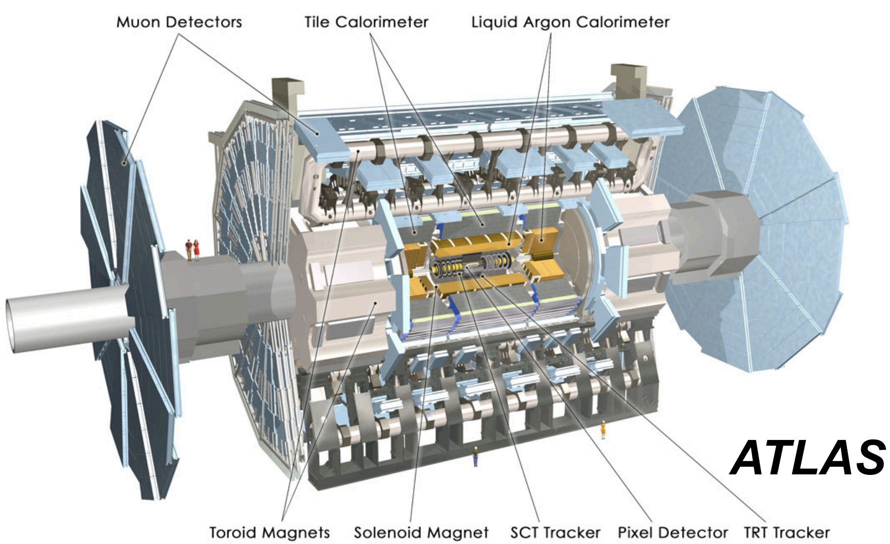
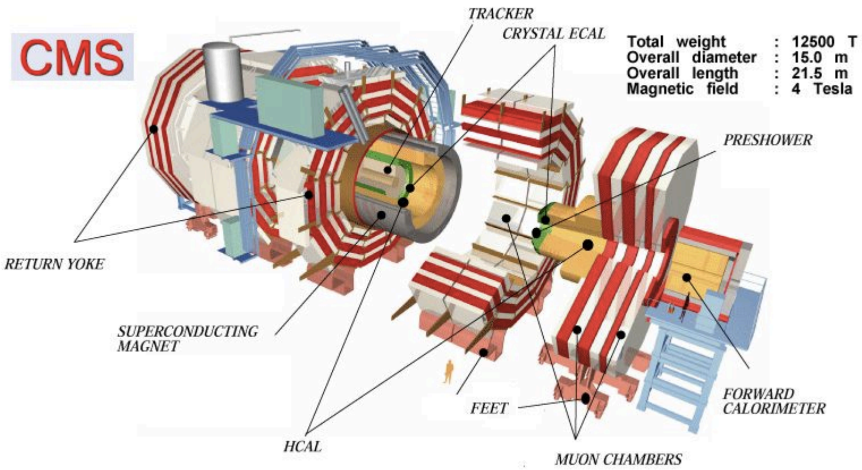
ATLAS and the LHC





- **ATLAS**
  - Air-toroid muon spectrometer
  - High precision calorimetry
    - Highly granular electromagnetic calorimeter up to $|\eta| < 3.2$
    - Hadronic tile calorimeter barrel and endcaps up to $|\eta| < 3.2$
    - Forward calorimeters for $3.2 < |\eta| < 4.9$, granularity of $\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.2$
  - Tracking coverage up to $|\eta| = 2.5$

ATLAS and the LHC



CMS

- Compact design
- Full silicon tracker
- Tracking coverage up to $|\eta| = 2.5$

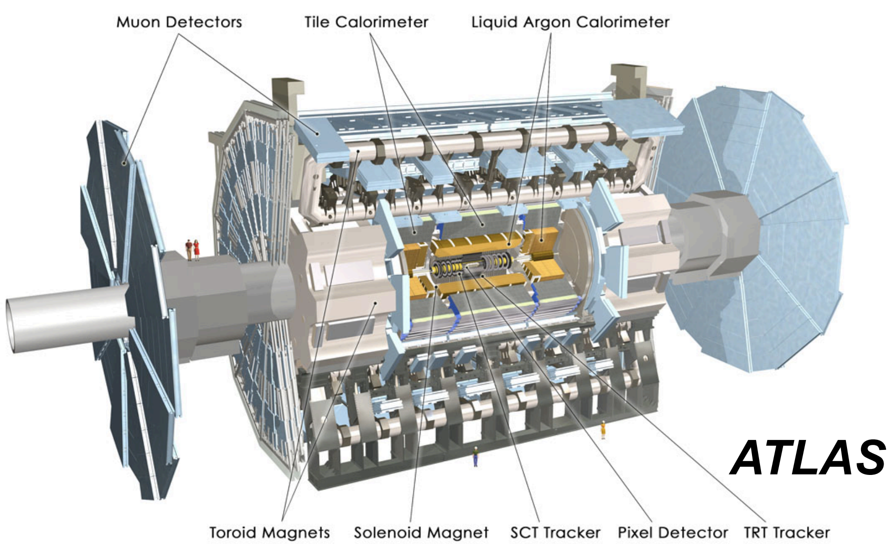
er

neter

er barrel

$|\eta| < 3.2$

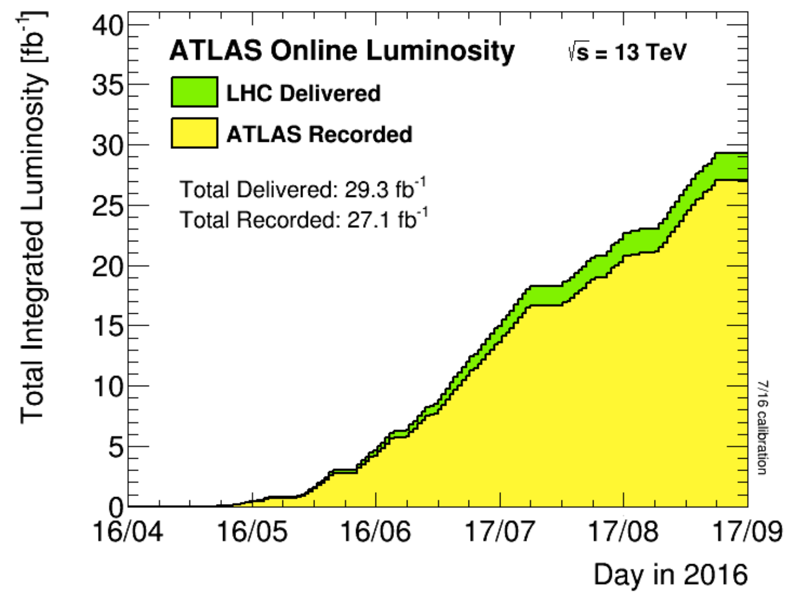
- Forward calorimeters for $3.2 < |\eta| < 4.9$, granularity of $\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.2$

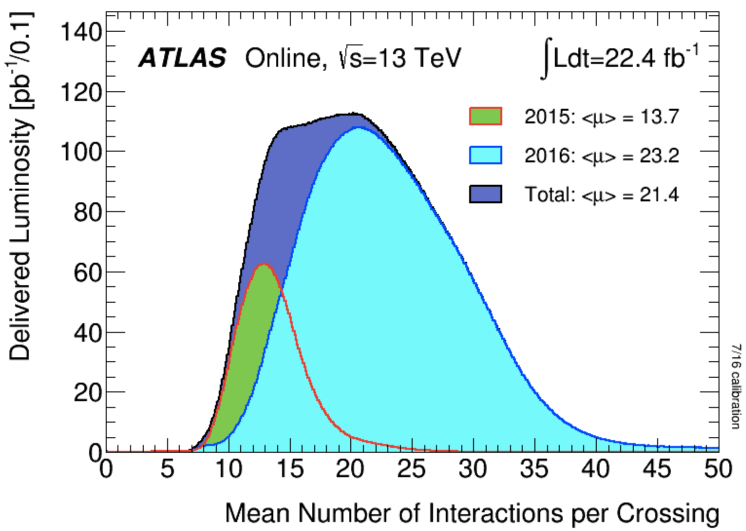


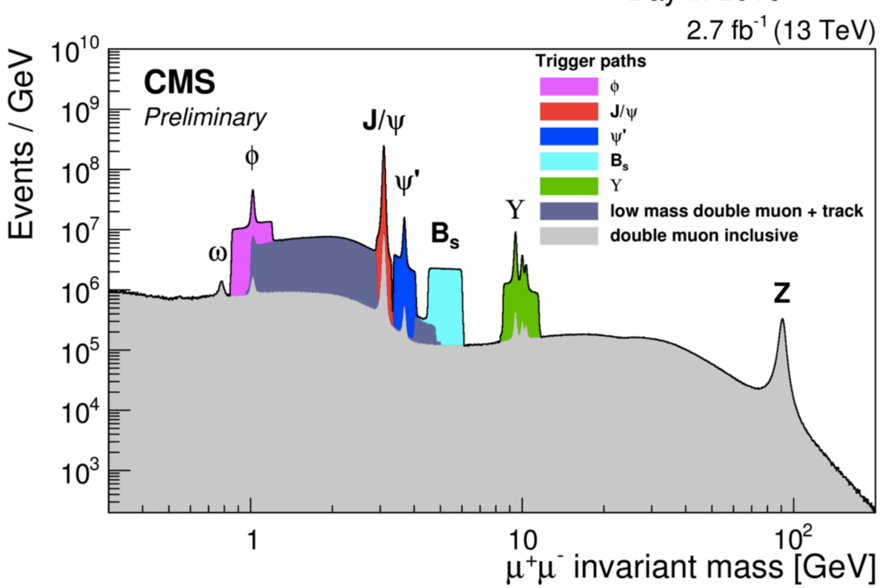
- Tracking coverage up to $|\eta| = 2.5$

ATLAS, CMS and the LHC

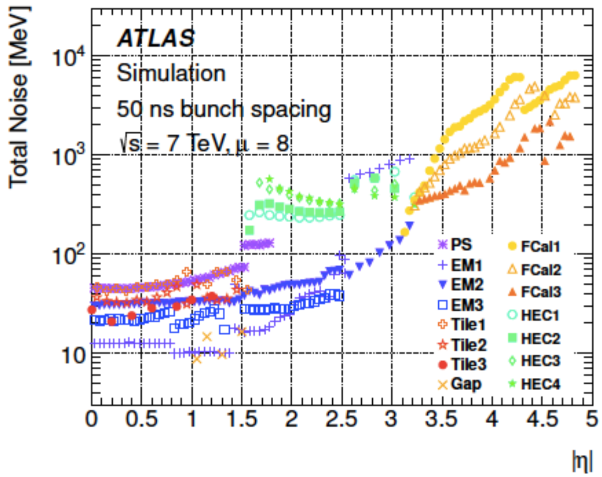
- The LHC is performing very well, as well as ATLAS and CMS with data taking efficiencies well above 90%
- ~30 fb-1 of proton-proton collisions at 13 TeV recorded at the moment
    - Results with up to ~15 fb-1 are public
- Impressive performance from all sub-detectors and reconstruction
    - ~50 years of particle physics covered shortly after the LHC restarting last year



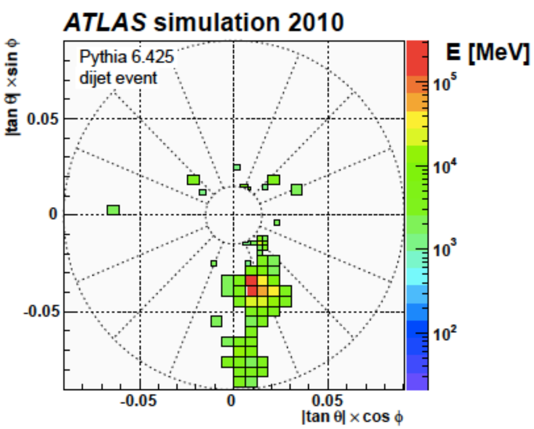




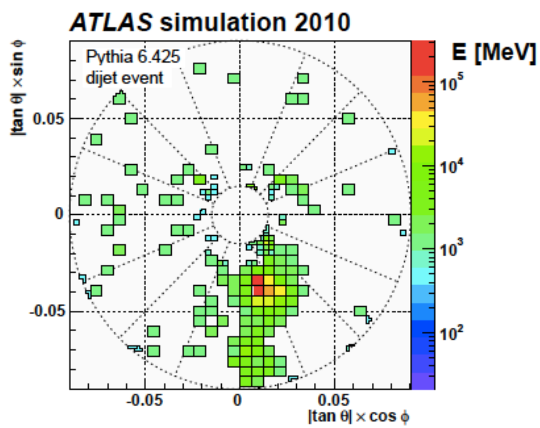
Inputs to jet finding: Topological Clusters



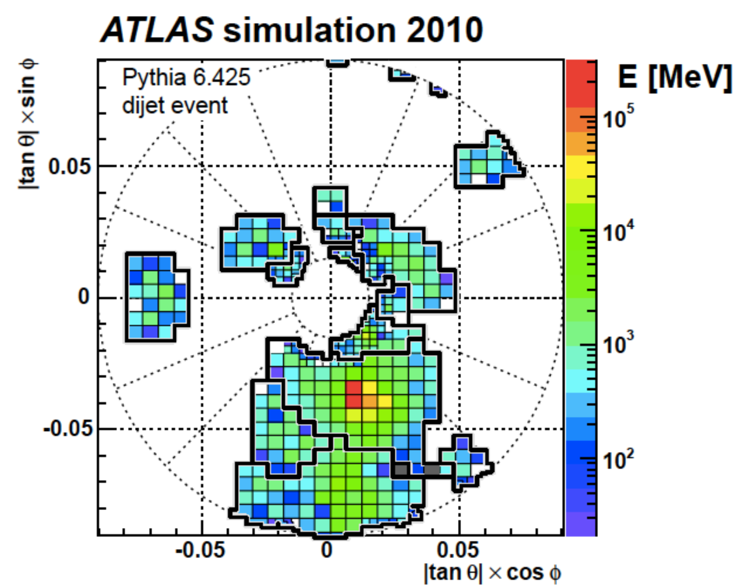
- ATLAS focuses on ‘topo-clusters’ as calorimeter input to jet finding
  - 3-dimensional clusters of calorimeter cells
  - Attempt to reconstruct particle showers in the calorimetry while suppressing noise contributions (electronic+pileup)



$E > 4\ \sigma_{noise}$



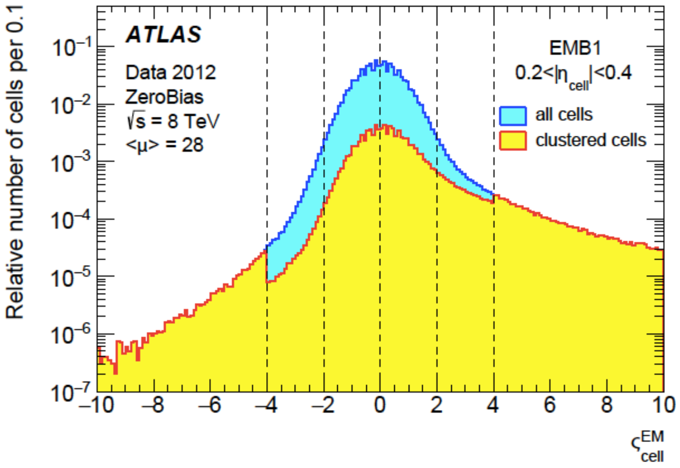
$E > 2\ \sigma_{noise}$



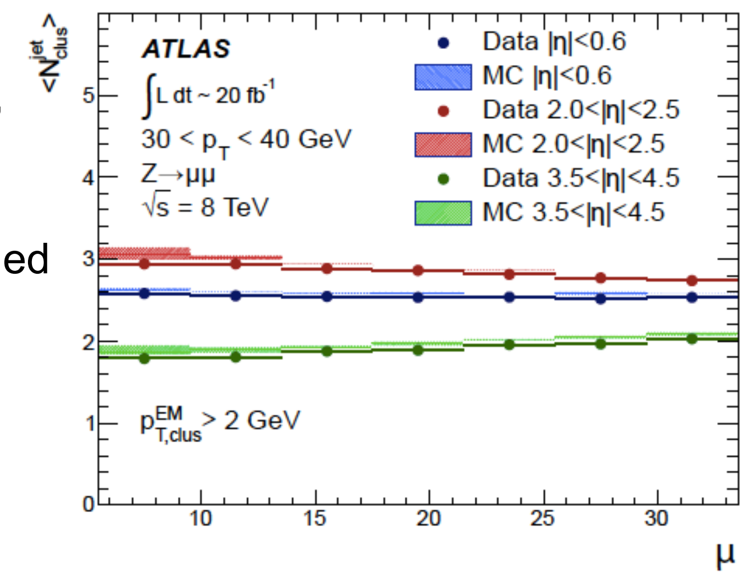
- Topo-clusters are treated as massless to avoid picking up fake jet-mass from showering

Inputs to jet finding: Topological Clusters

- Result in significant reduction of number of cells entering jet reconstruction
- Average number of topo-clusters with a significant transverse momentum (p_T) within a jet robust against pileup
- For small radius jets ATLAS keeps topo-clusters on the electromagnetic scale in Run-2
  - Sophisticated jet-level corrections in place
- For large radius jets and substructure variables, the so called Local Hadron Calibration is used, correcting topo-clusters for:
  - invisible and lost energy for clusters classified as hadronic
  - energy losses due to noise thresholds
  - energy lost outside the active calorimeter volume



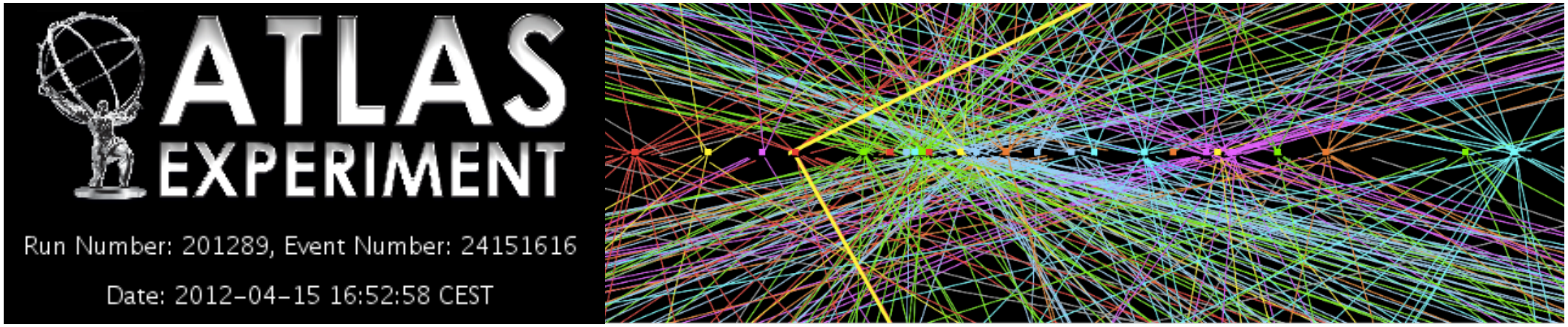
(a) First sampling EMB1 ($0.2 < |\eta_{\text{cell}}| < 0.4$)



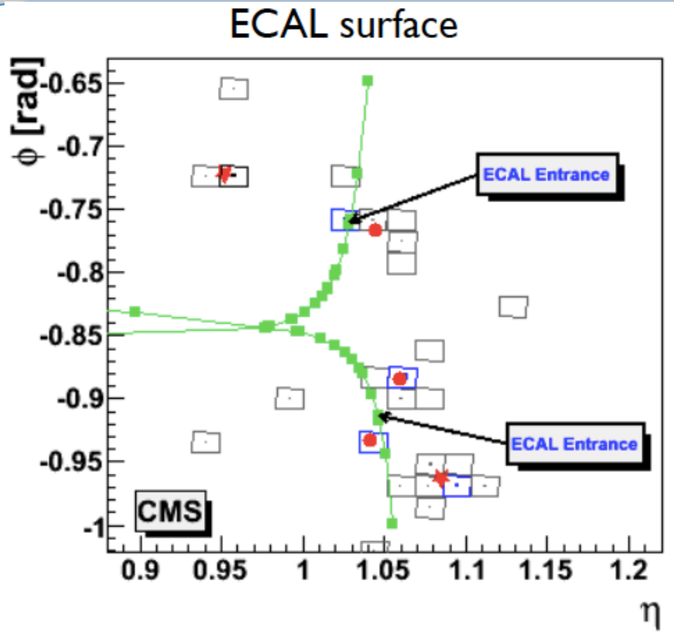
Inputs to jet finding: Tracks

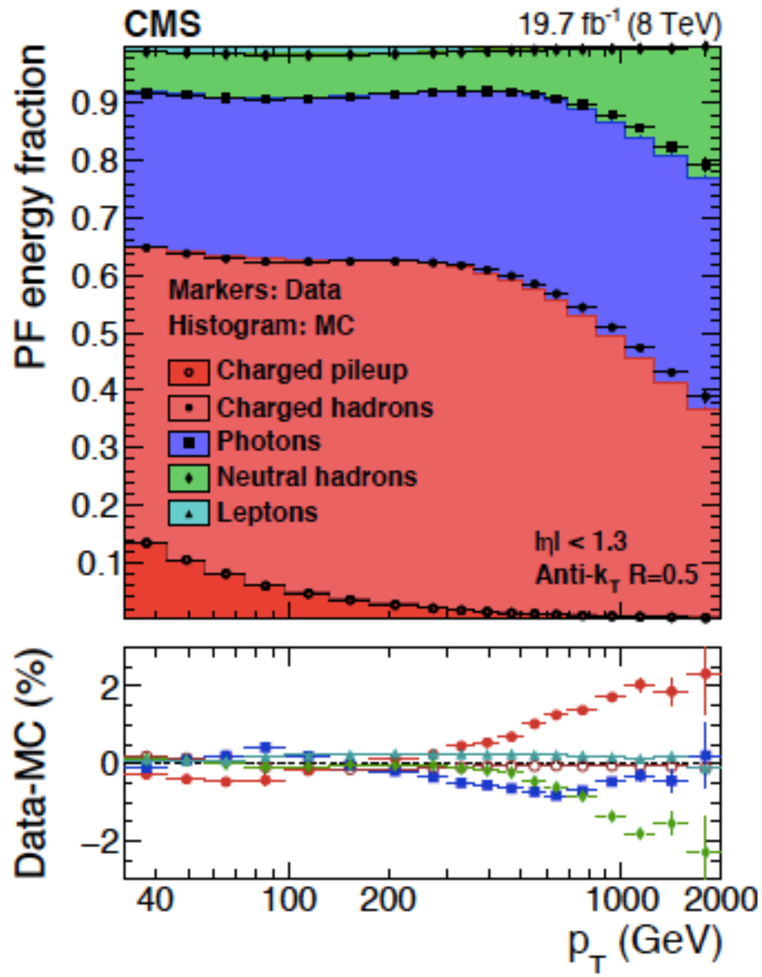
- Inner detector charged tracks with p_T > 500 MeV are ‘ghost associated’ to jets
    - allows the use of charged tracks (originating from hard scatter vertex) over calorimeter pT and similar for pileup suppression
    - track derived variables and jet moments are used to refine the jet calibration, improve the jet energy resolution and in some physics analyses
- Track segments in the muon system are associated to jets to get a handle on longitudinal shower leakage

- ‘Particle flow’ objects as input for jet finding are a hot R&D topic in ATLAS, but no public results yet - stay tuned!



CMS: Particle flow objects

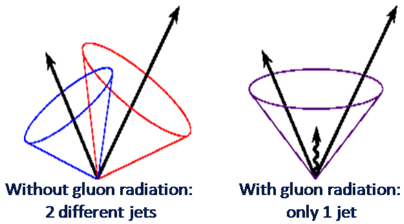


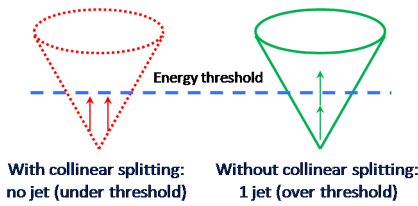


- Tracking and calorimeter information is combined to reconstruct particle flow objects
- Profit from tracking resolution at low momenta
- 'Overlap' removal requires dedicated pre-scriptions, e.g. for Bremsstrahlung clusters from electrons
- Added benefit: Can remove charged pileup after track-cluster matching

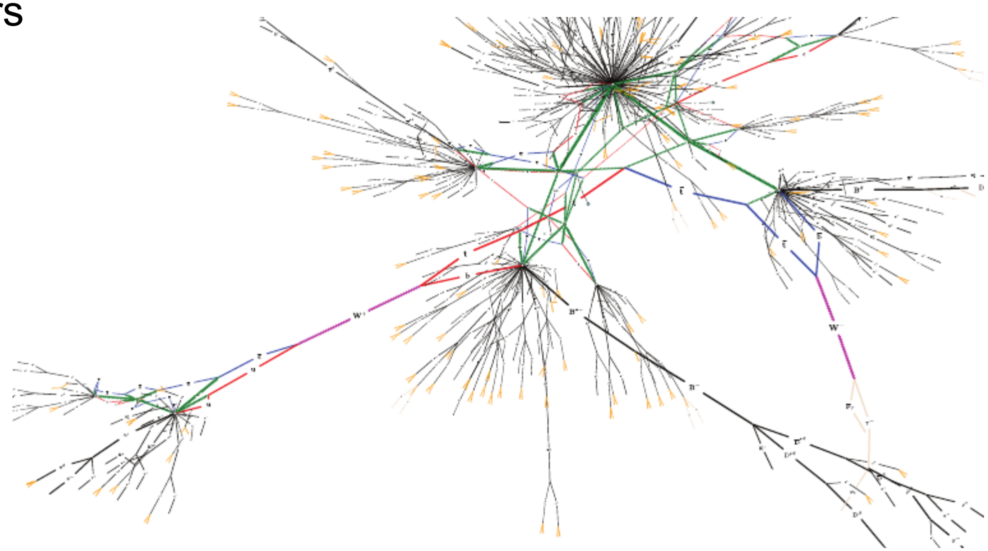
Jet Finding

- Jet finding wish list:
  - Theoretically well behaved
    - Infrared and collinear safety
  - Computationally feasible
  - Detector independent
    - Apply to reconstructed objects, particle level, final state partons, …





- **Jets are not 'fundamental' objects like isolated charged leptons**
  - Specific jet-finding algorithms provide specific view on the activity of an event
  - Different processes and measurements ask for different algorithms and parameters



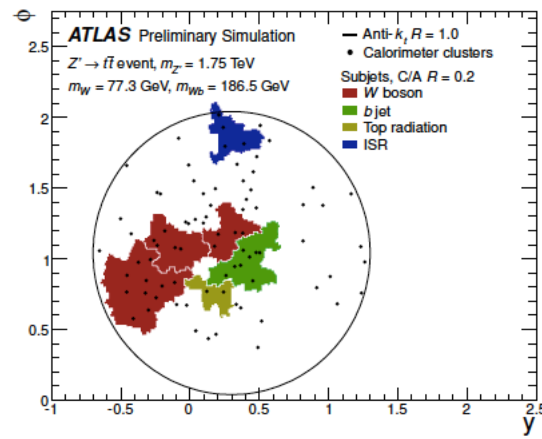
Jet Finding: kt, antiKt and C/A

- Three jet algorithms used by ATLAS, belonging to the same (infrared and collinear safe) class of clustering algorithms
- Typically used in the following cases:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

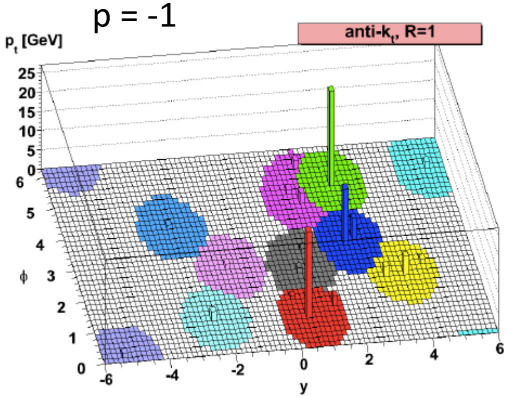
$$d_{iB} = k_{ti}^{2p} \, ,$$

	small-R R = 0.4	large-R jets R = 1.0	R = 1.2	sub-jets R = 0.2
p = -1, antiKt	X	X		
p = 0, Cambridge/Aachen			X	X
p = 1, Kt				X

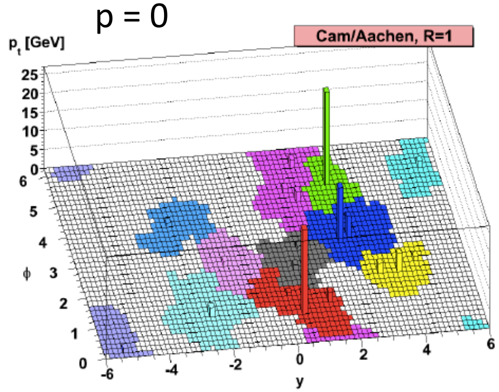


'Ghost association': for jet finding tracks are treated as 4-vectors with infinitesimal magnitude, being picked up by the jet algorithms

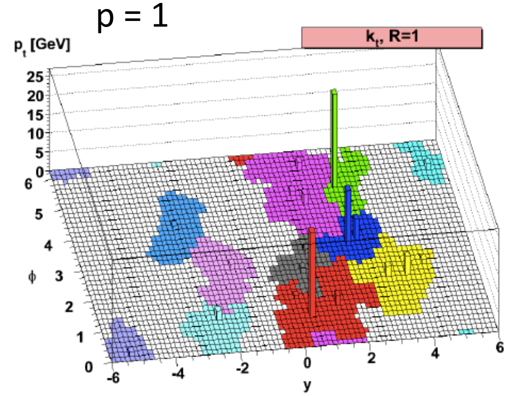
p = -1



p = 0



p = 1



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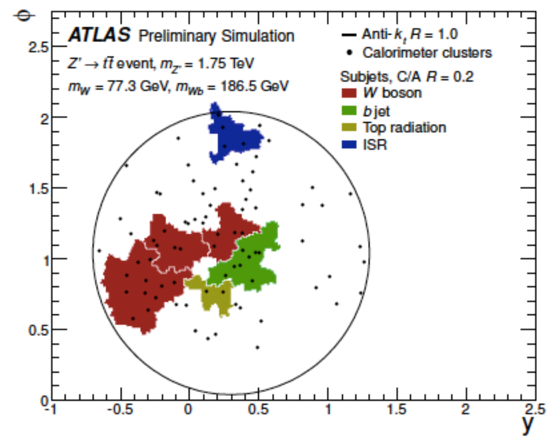
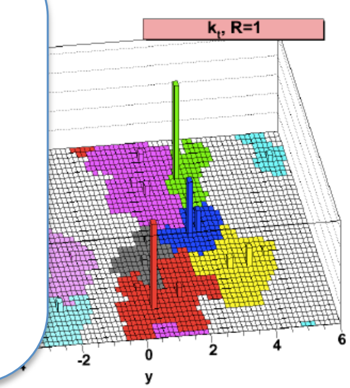
	small-R	large-R jets		sub-jets
	R = 0.4	R = 1.0	R = 1.2	R = 0.2
p = -1, antiKt	X	X		
p = 0, Cambridge/Aachen			X	X
p = 1, Kt				X

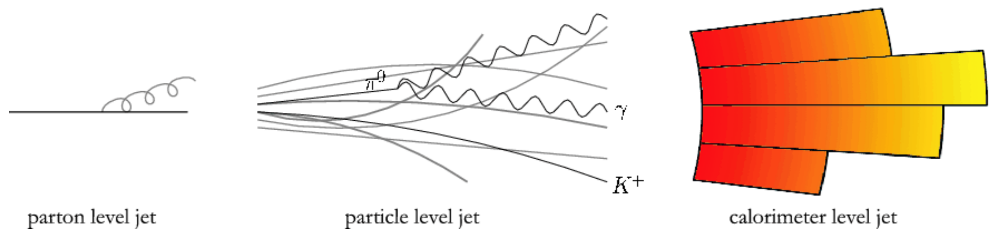


'Ghost association': for jet finding tracks are treated as 4-vectors with infinitesimal magnitude, being picked up by the jet algorithms

CMS	small-R	large-R jets		sub-jets
	R = 0.5	R = 0.8	R = 1.5	R = 0.2+
p = -1, antiKt	X	X		
p = 0, Cambridge/Aachen		X	X	X
p = 1, Kt				X



Calibration references

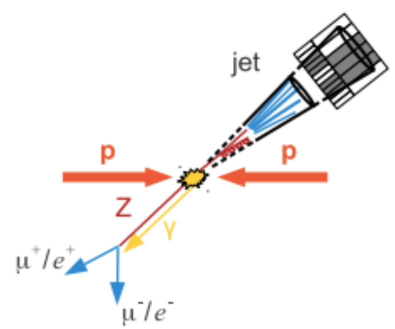


- The main reference for jet calibration are ‘particle jets’ in samples of simulated events
  - Apply jet finding on stable (cτ > 1 cm) particles, excluding muons and neutrinos

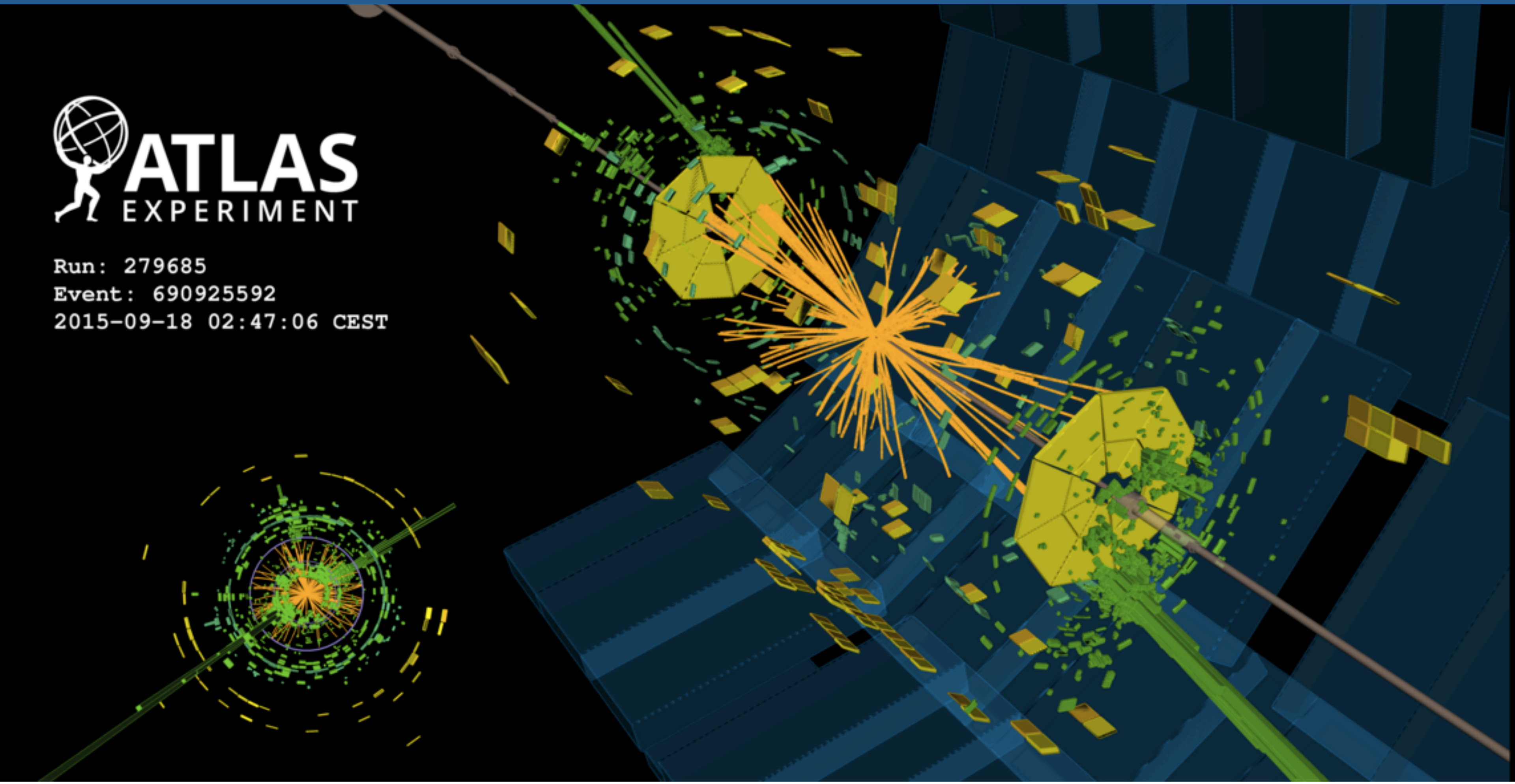
CMS
- Apply jet finding on stable (cτ > 1 cm) particles, excluding and neutrinos

  - Corresponds well to visible energy in inclusive jet selections, e.g. light quark and gluon jets
    - Depending on physics use case, other definitions can be better justified, but the ‘universal’ Jet Energy Scale corrections are derived from QCD jet production samples in any case, where differences in definition have a negligible impact

- **Typical reference objects in data:**
  - isolated photons and Z(->ll) boson

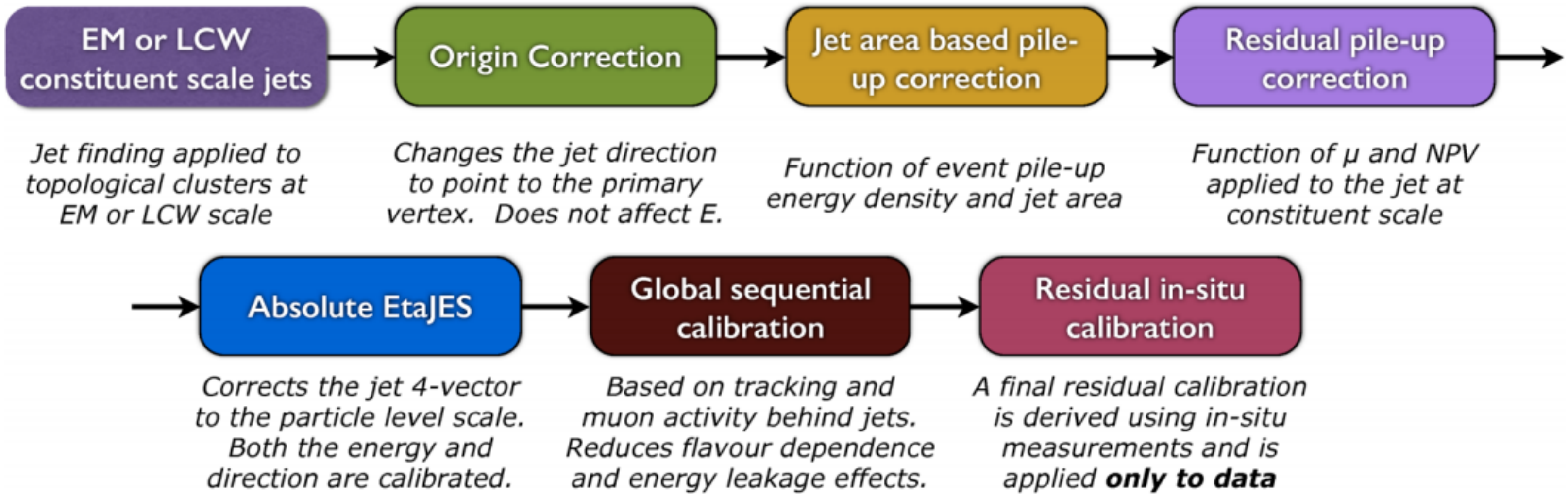


Small Radius Jet Calibration and Performance



Recorded event with dijet system with a mass of 8.8 TeV

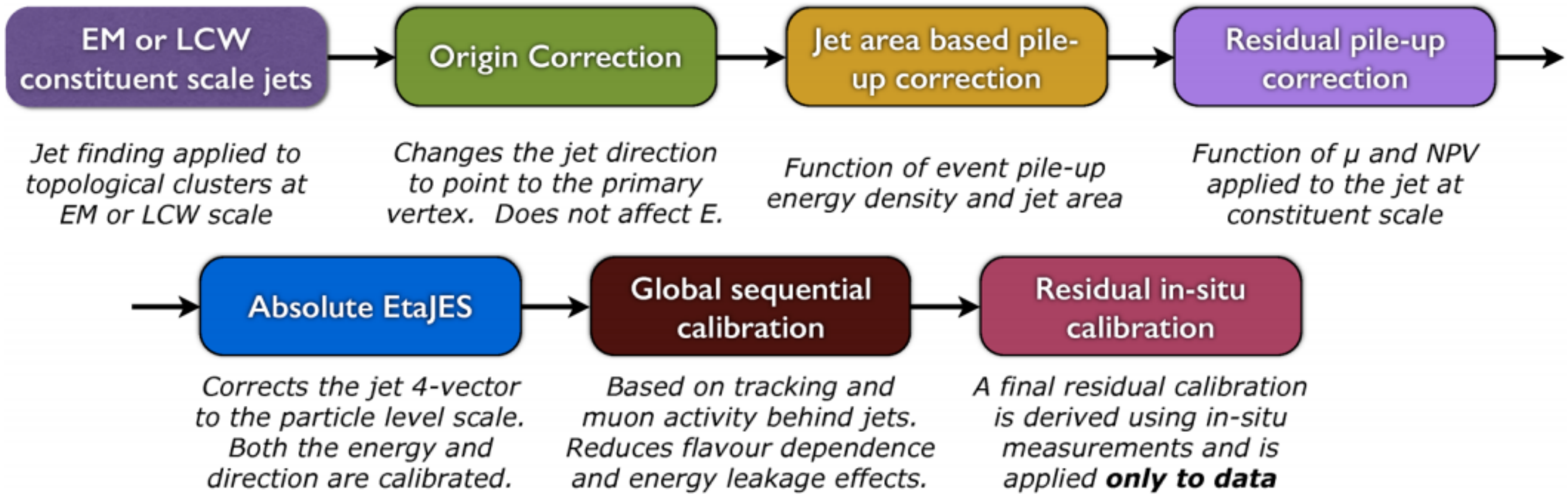
Small-R Jet Calibration

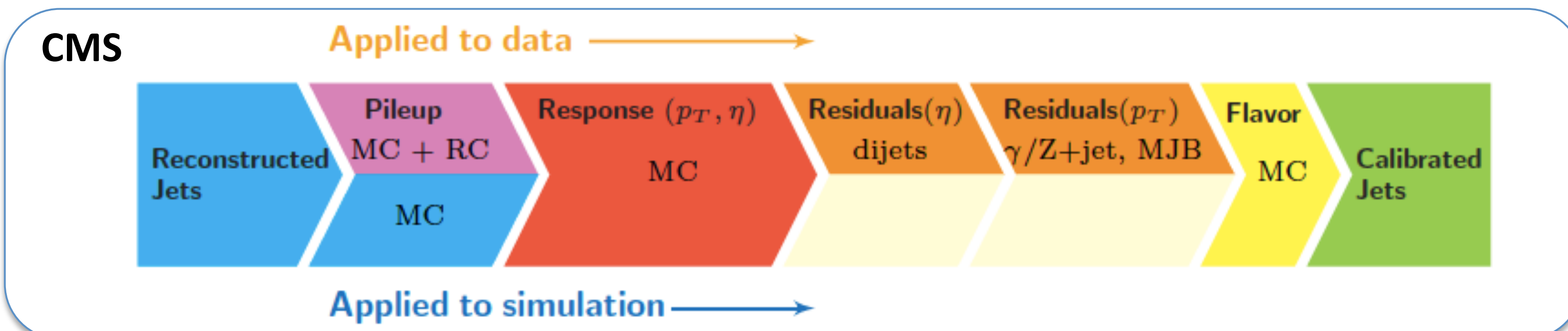


- Goals of the ATLAS jet calibration
  - Calibrate the jet energy scale to the particle level of the hard interaction
  - Reduce the jet-to-jet variations, resulting in a good jet energy resolution
  - Achieve the above two goals with as small an uncertainty as possible

- The jet calibration is derived and applied in a number of steps, the last one of these only being applied to jets in data

Small-R Jet Calibration





- The jet calibration is derived and applied in a number of steps, the last one of these only being applied to jets in data

(Jet area based) pileup corrections

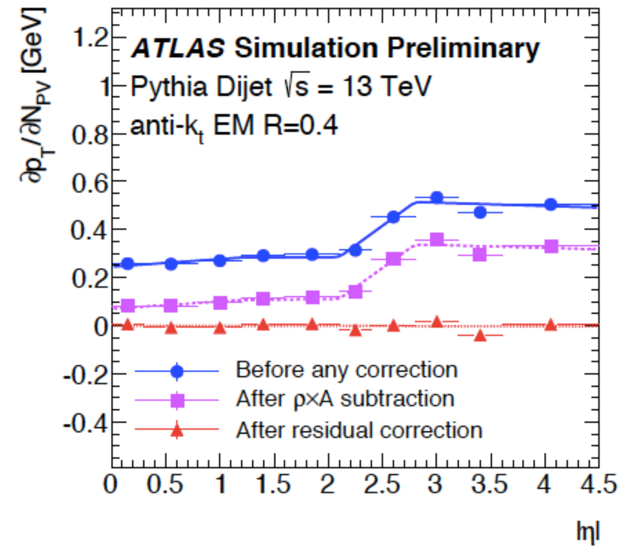
- Pileup is characterized using two variables
  - <μ> = expected average number of interactions per bunch-crossing
  - NPV = number of reconstructed primary vertices
- In addition the 'pile-up' pT density ρ is reconstructed for every event
  - Fill the event (up to |η| < 2.0) with 'ghosts' and reconstruct kT 0.4 jets, then take

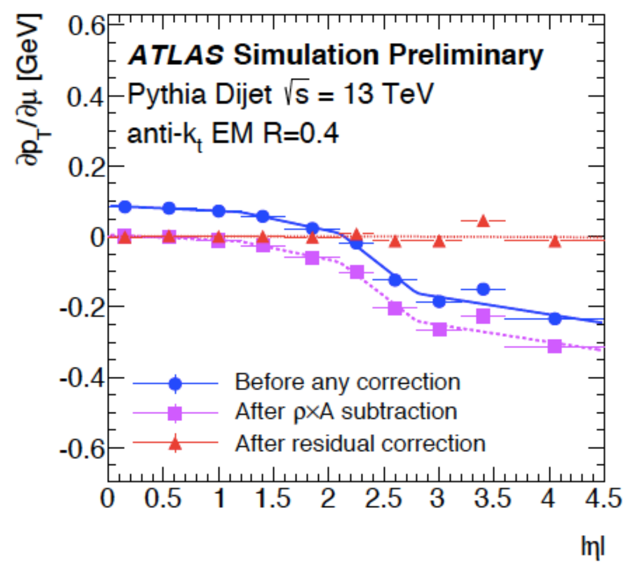
$$\rho = \text{median}\left\{\frac{p_{\mathrm{T},i}^{\mathrm{jet}}}{A_i^{\mathrm{jet}}}\right\}$$

  - While this is usually called the pile-up density, it also includes the underlying event
- Individual jets are corrected first, fully data-driven, using ρ and their active area

$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}}^{\mathrm{jet}} - \rho \times A^{\mathrm{jet}}$$

- A simulation based residual correction is then applied, as a function of <μ>, NPV and jet pseudorapidity η





(Jet area based) pileup corrections

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  - <μ> = expected average number of interactions per bunch-crossing
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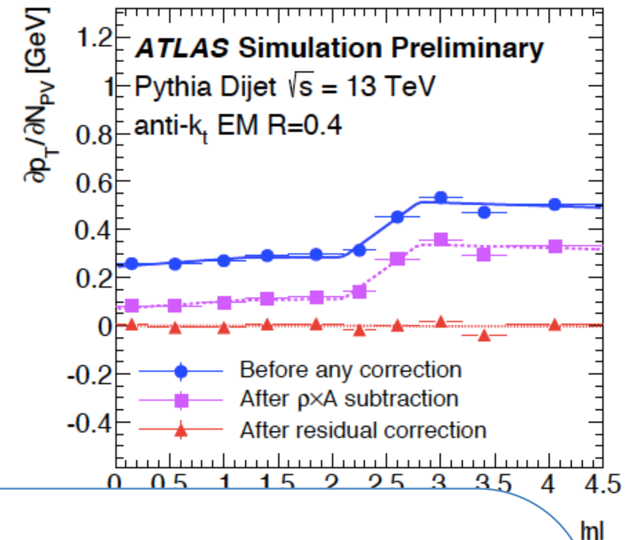
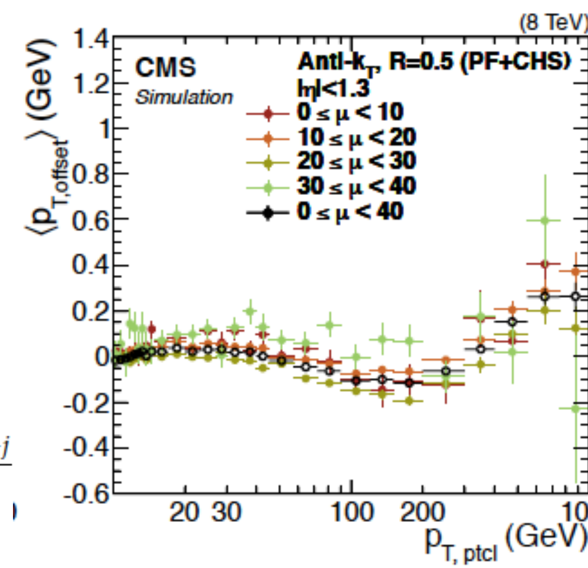


CMS

- Fill the event (up to |η| < 4.7) with kT 0.6 jets to get ρ
- the area based and residual correction are performed in one step, including a correction to add the underlying event density back in

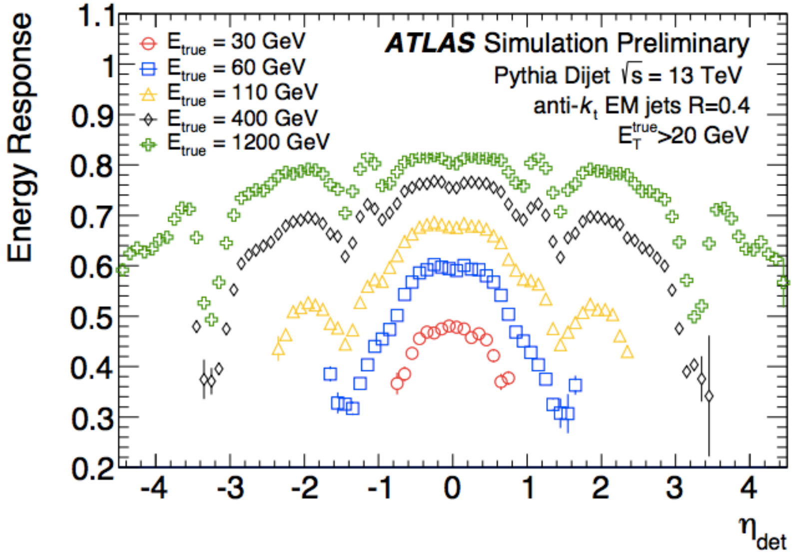
$$C_{\text{hybrid}}(p_{\text{T,uncorr}}, \eta, A_j, \rho) = 1 - \frac{[\rho_0(\eta) + \rho\beta(\eta)\,(1 + \gamma(\eta)\log(p_{\text{T,uncorr}}))]\,A_j}{p_{\text{T,uncorr}}}$$

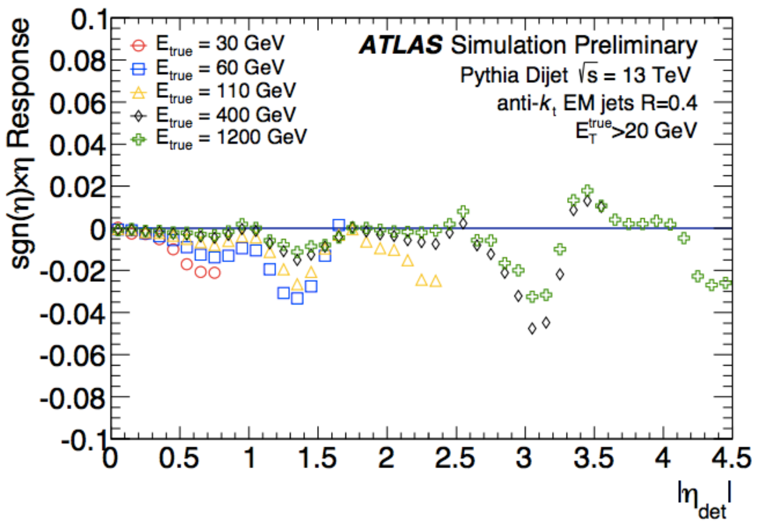


Absolute EtaJES

- With input clusters on the em-scale, there is
  - Significant dependency of the jet energy response on the jet energy and pseudo-rapidity
  - Bias of the jet axis in areas where the energy response changes rapidly with pseudorapidity

- This is corrected by the so-called '**EtaJES**' correction, derived by fitting and inverting the response functions in samples of simulated QCD events
  - The reference are particle level jets, obtained from all 'stable' particles in the event, excluding muons and neutrinos





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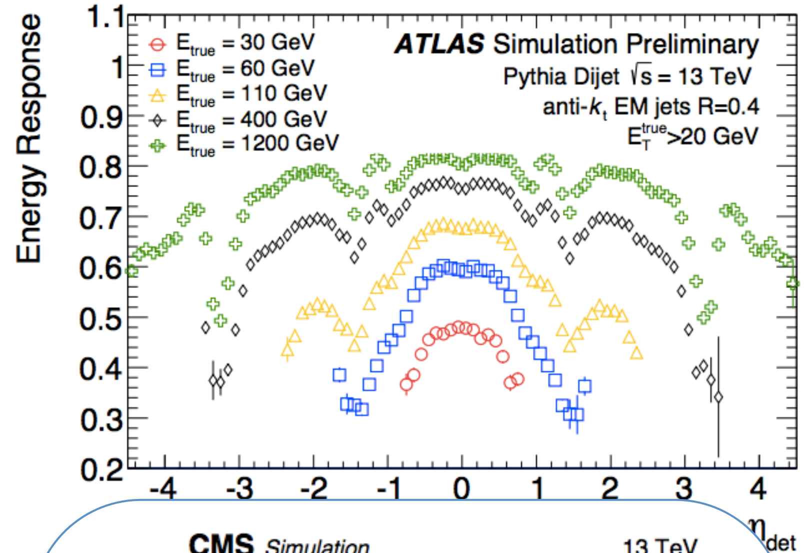
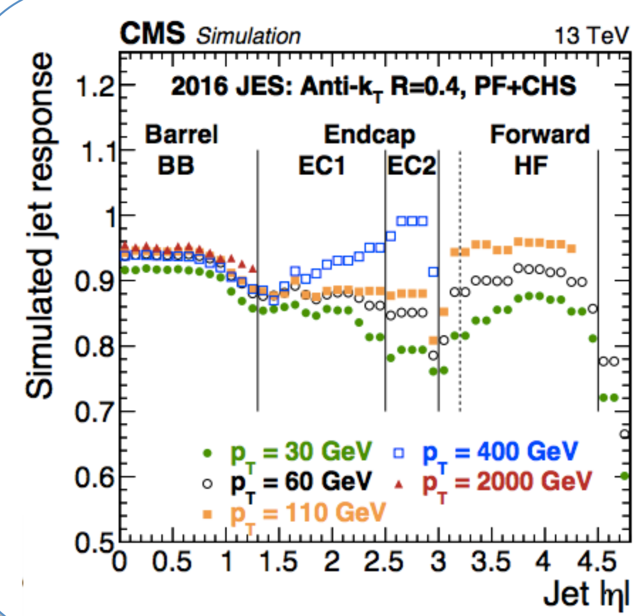
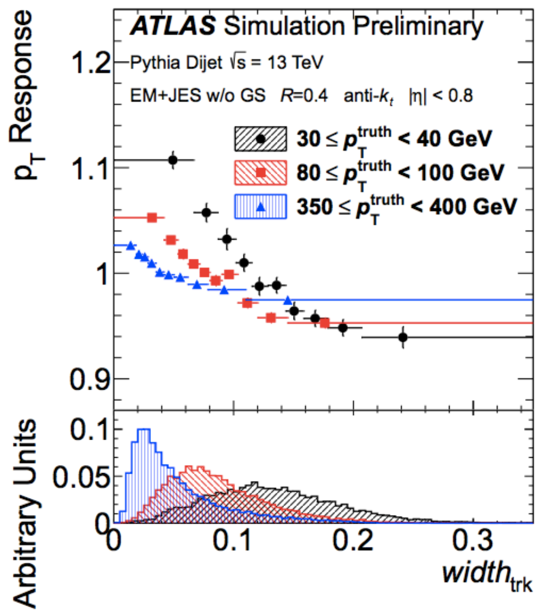
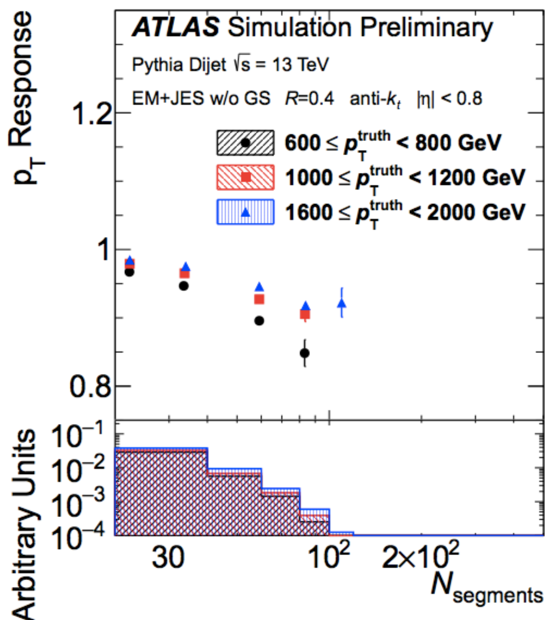




ATLAS Global Sequential Calibration





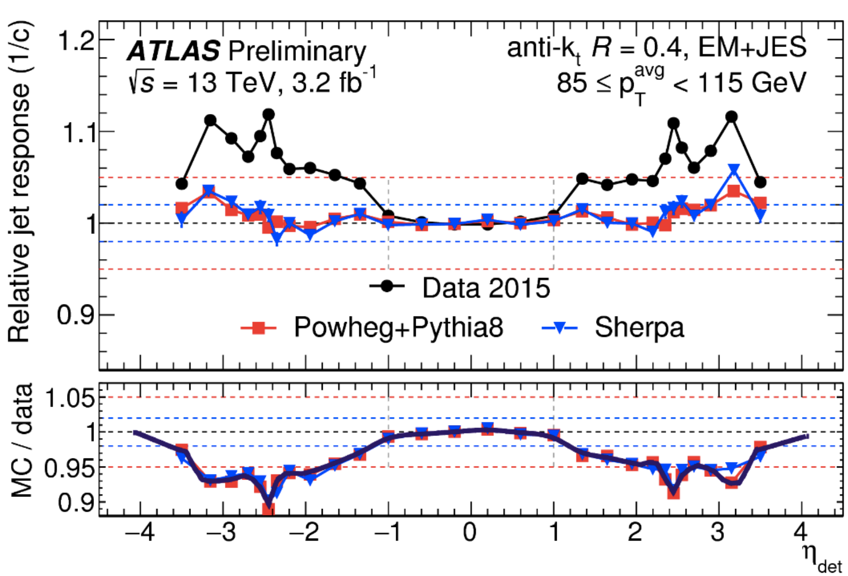
- GSC parameterizes the jet response as a function of jet p_T, η and one additional property X
  - By design the mean jet response is not affected, but the jet energy resolution is improved, and the dependency of the response on the jet flavour (gluon vs. quark) is significantly reduced

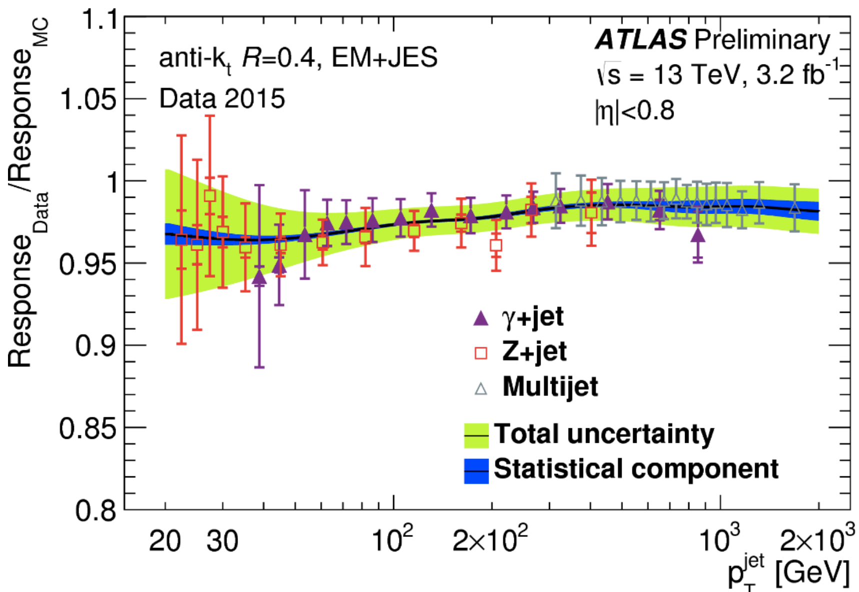
- Derived and applied sequentially for several properties X
  - fraction of the jet energy deposited in the first layer of the hadronic calorimeter
  - fraction of the jet energy deposited in the third layer of the EM calorimeter
  - number of inner detector tracks associated with the jet with pT> 1GeV
  - The 'trackWIDTH' of the jet based on the associated tracks
  - number of segments behind the jet in the muon chambers

Residual in-situ correction

- Due to differences in simulated events compared to data in e.g.
  - simulation of the underlying event, pile-up activity and jet formation, detector material

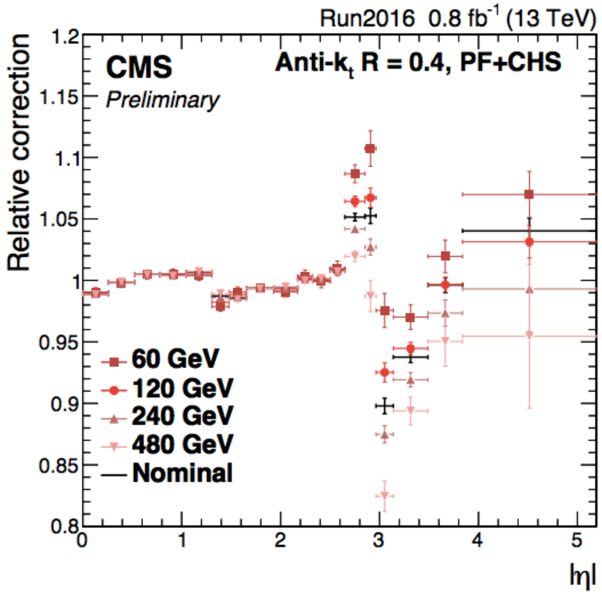
  an additional correction is required to get jets in both data and simulation to the same reference scale
- Two components, both applied to data only
  - Relative (inter-)calibration in pseudorapidity, derived from dijet events
  - Absolute scale correction from γ/Z+jet and multijet events
- The Run-2 absolute in-situ correction is sizable compared to Run-1, due to a number of changes in simulation, most prominently from QGSP-BERT to FTFP-BERT

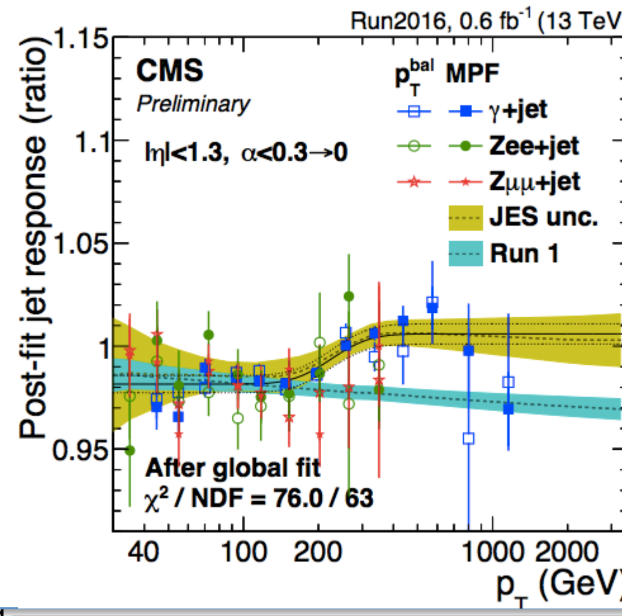


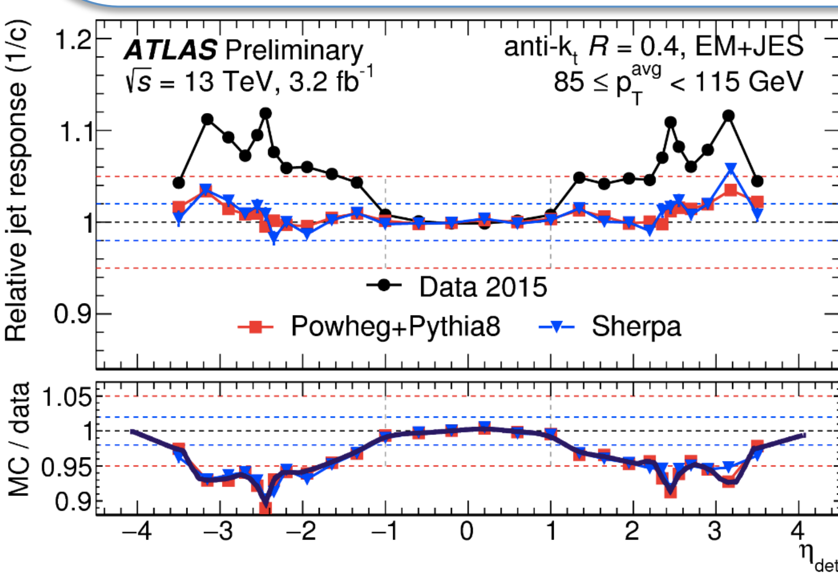


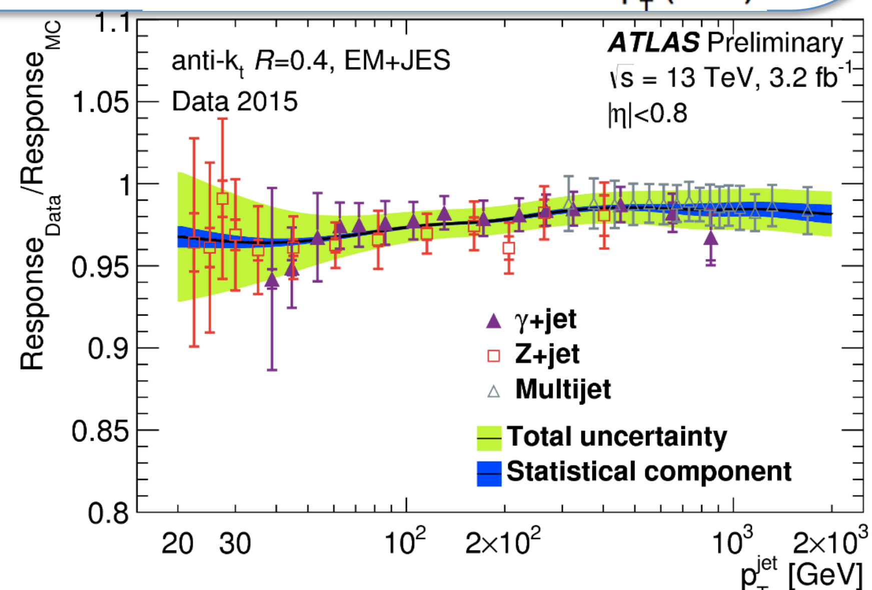
Residual in-situ correction

CMS



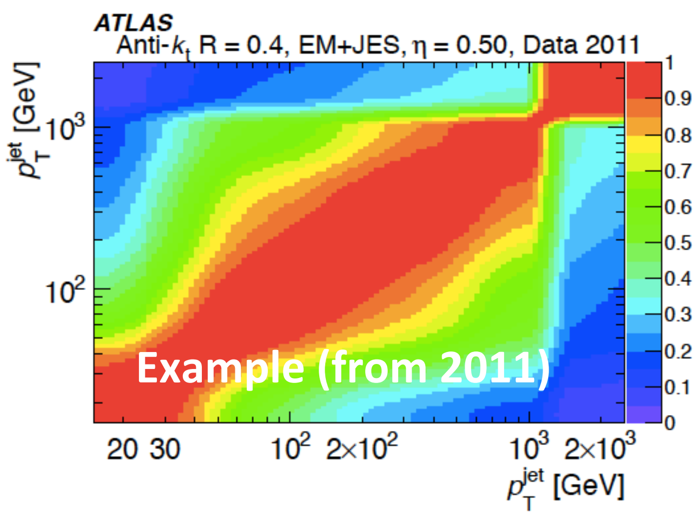


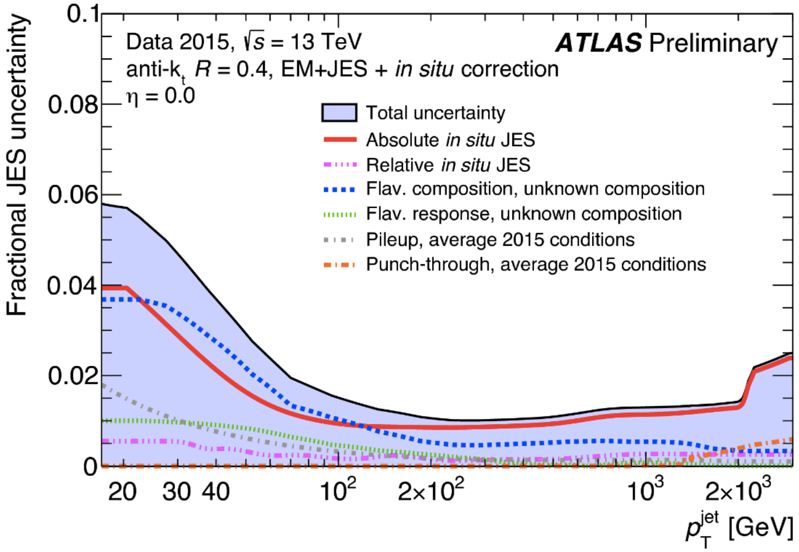


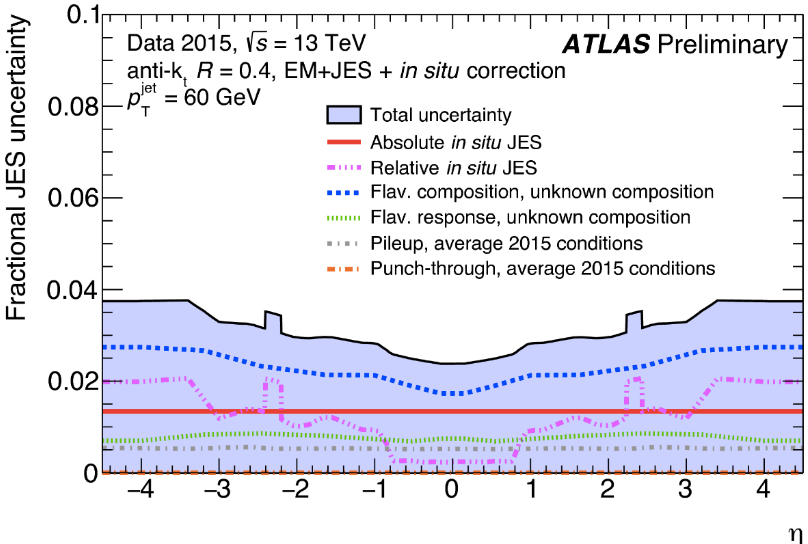


Jet Energy Scale Uncertainties

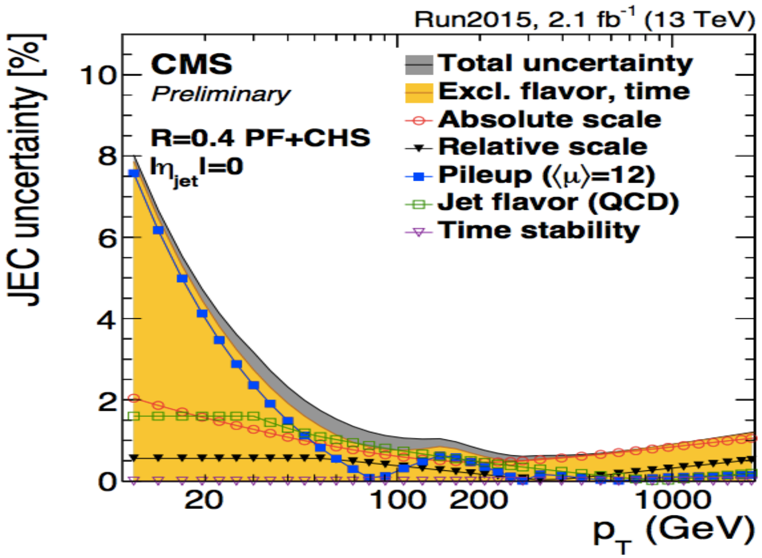
- Uncertainties on the jet energy scale result from a number of sources
  - Physics and detector simulation
  - Statistical uncertainties
  - Uncertainties due to differences in quark/ gluon jet fractions and pileup conditions
- Uncertainties and all correlations are described by a set of about 70 uncertainty components
  - Typically 'reductions' adequately describing the correlations are in use by analyses, bringing the number of terms to one digit

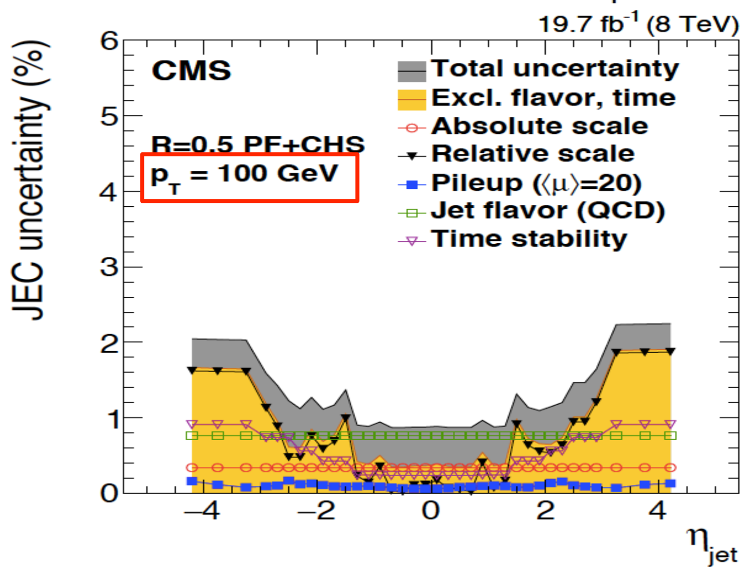


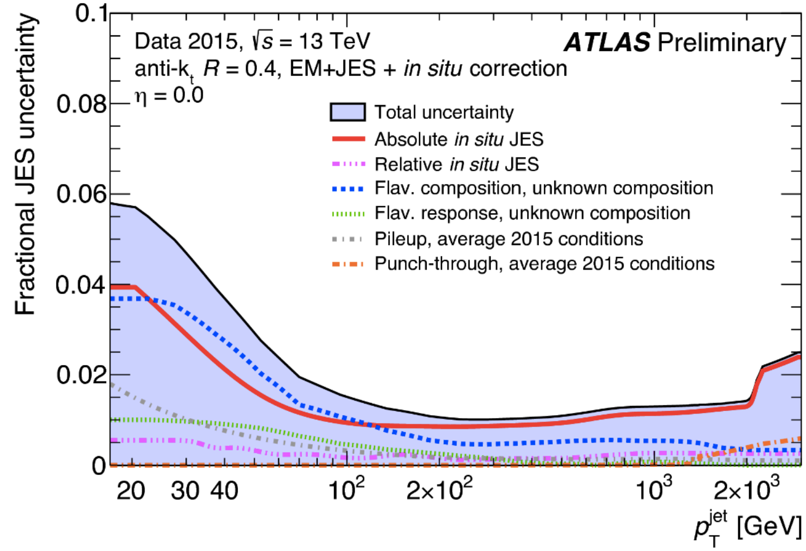


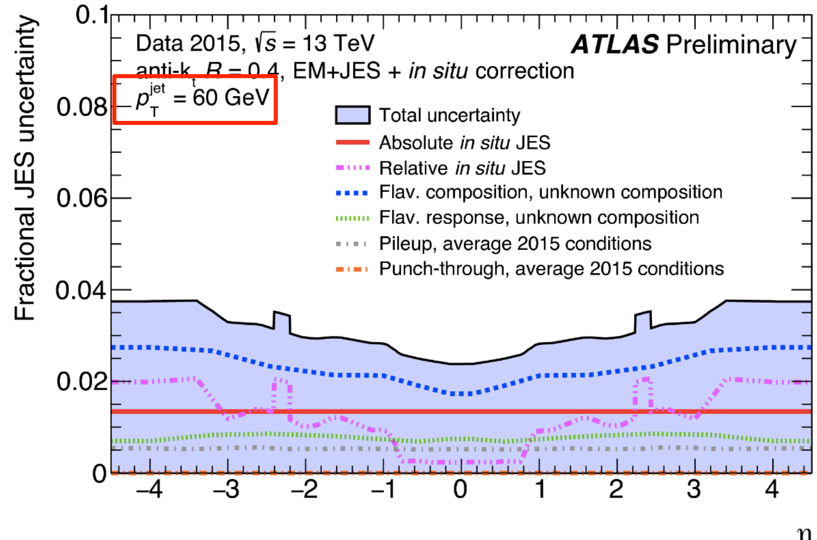


Jet Energy Scale Uncertainties







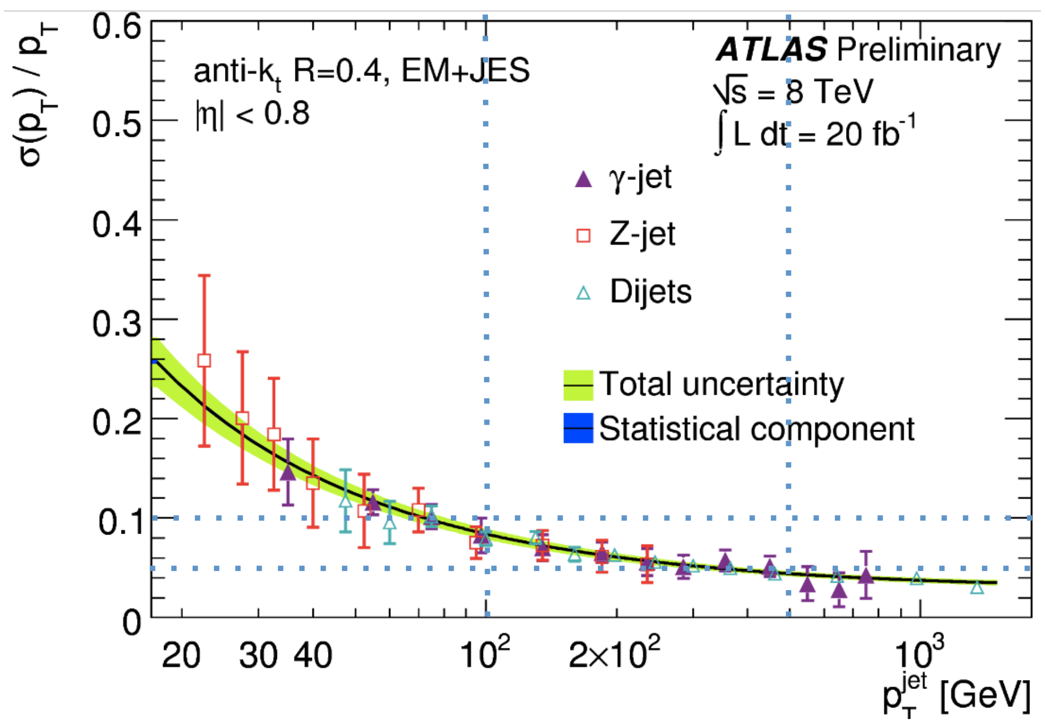


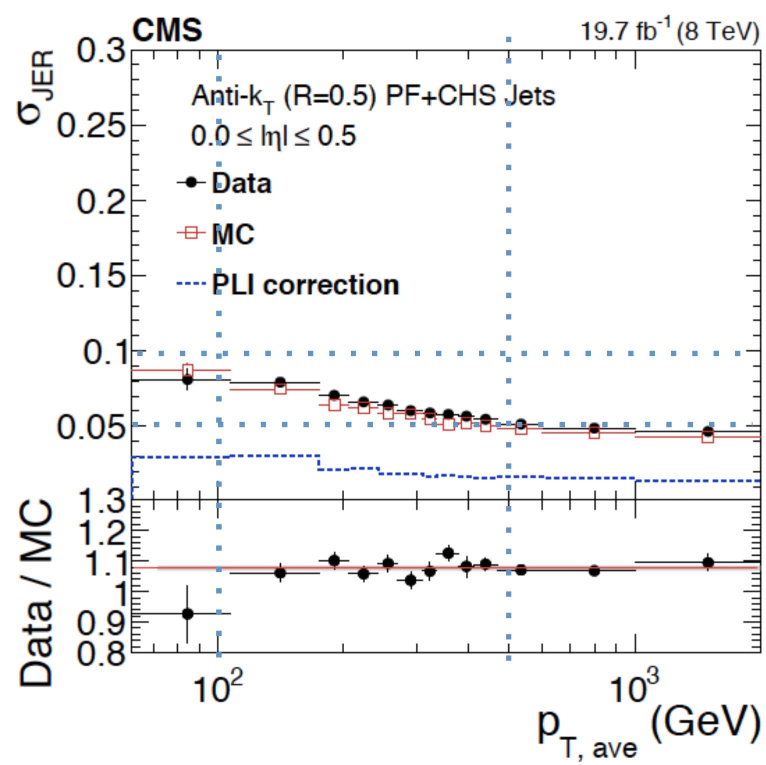
Small-R jet resolution

- The jet energy resolution can be determined from data, for example using QCD dijet events and the asymmetry

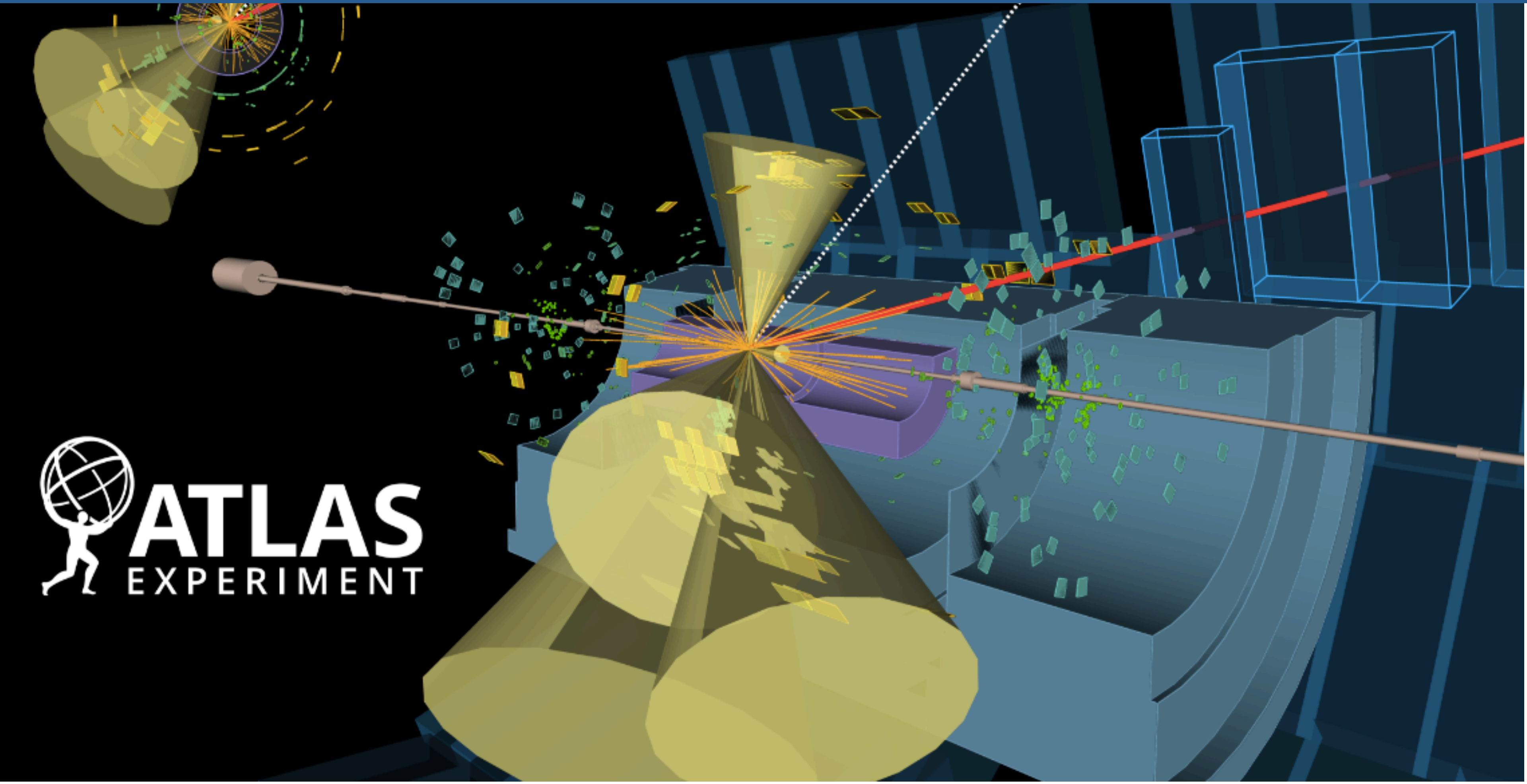
$$\mathcal{A} = \frac{p_{\mathrm{T,1st\ jet}} - p_{\mathrm{T,2nd\ jet}}}{p_{\mathrm{T,1st\ jet}} + p_{\mathrm{T,2nd\ jet}}} \qquad \sigma_{\mathcal{A}} k_{\mathrm{rad}} = \frac{\sigma_{\mathrm{JER,probe}}}{2} \oplus \frac{\sigma_{\mathrm{JER,tag}}}{2} \oplus \sigma_{\mathrm{PLI,dijet}}$$

where k_{rad} is a correction to zero radiation, σ_{PLI} the resolution of the particle level imbalance





Large-R Jets, Substructure and Object Tagging



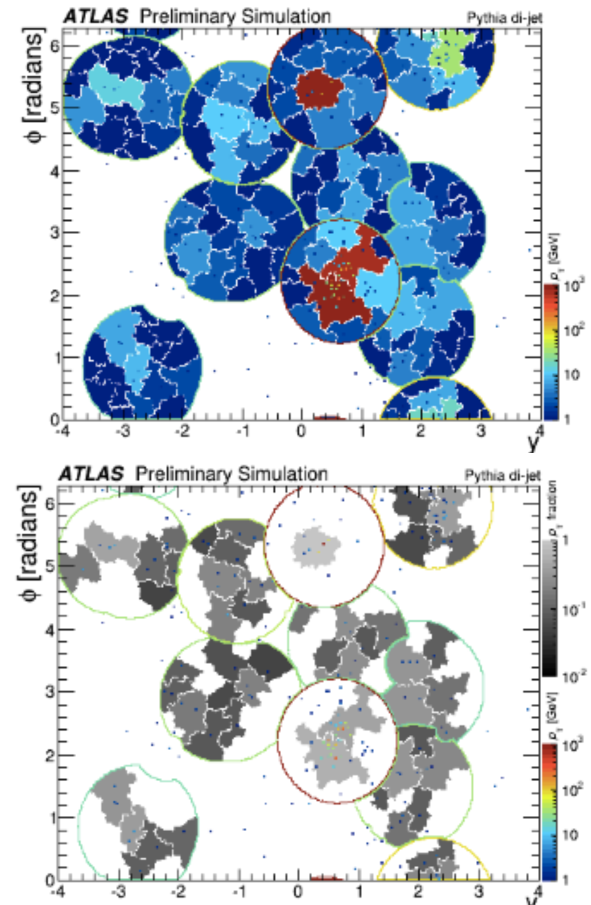
Recorded event with a top quark candidate with a pT of 600 GeV

Large-R jets and grooming

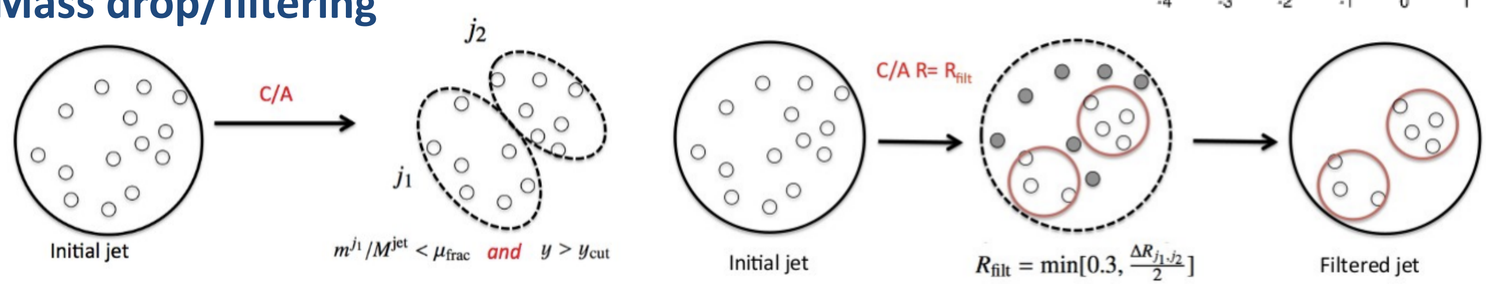
- Heavy objects with high pT decaying hadronically very common in LHC analyses
- Jet grooming: get rid of softer components of jet to get constituents from hard scatter
  - Search for boosted objects inside a large-R jet

- The most common approaches to reconstruct properties of the heavy objects in ATLAS are
  - ‘Reclustering’ antiKt 0.4 jets into large-R jets
  - ‘Trimmed Jets’ - reconstruct antikT R = 1.0 jets, trim by removing all R = 0.2 subjets with less than 5% of the large-R jet p_T
  - ‘Mass-drop/filtered Jets’, reconstruct C/A R = 1.2 jet, filter with a BDRS procedure

Trimming

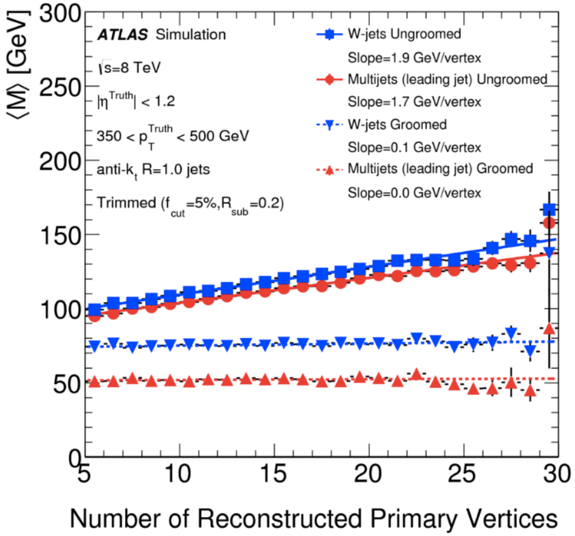


Mass drop/filtering

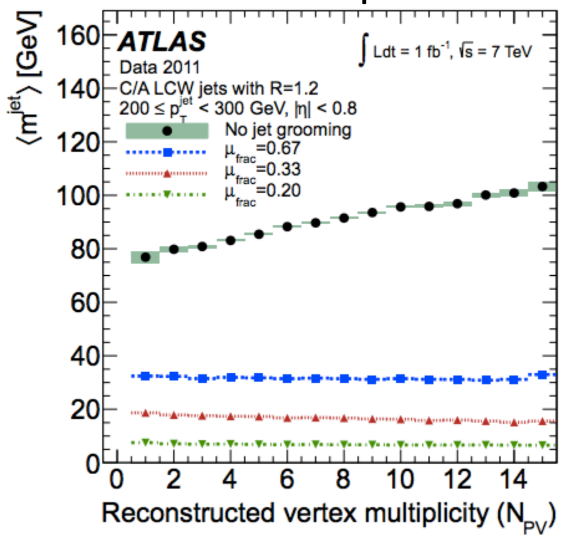


Large-R jets and grooming

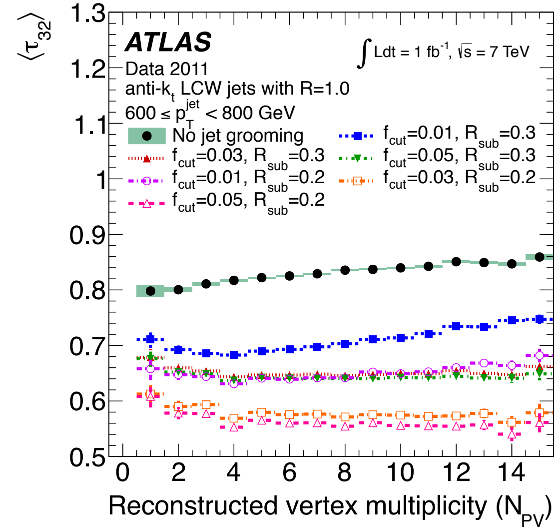
trimmed



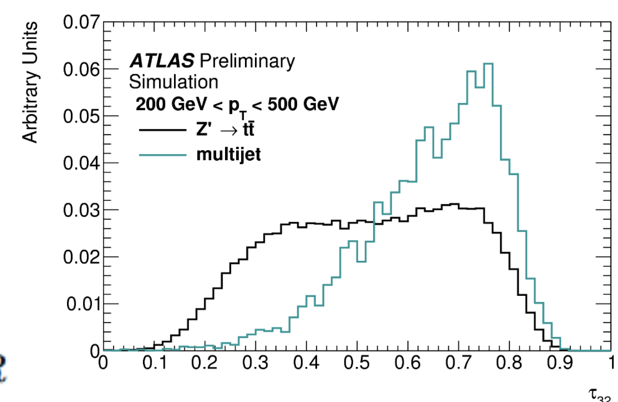
mass-drop filtered



trimmed



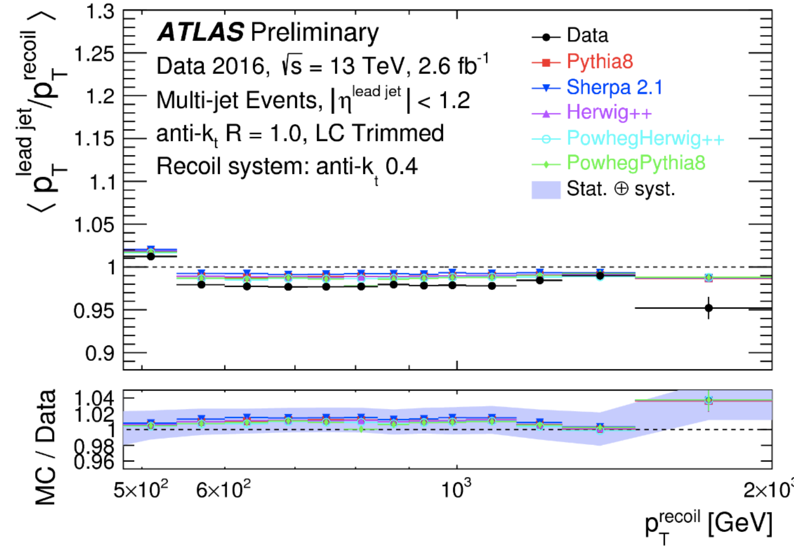
- Goal: Reconstruct observables of the 'real' boosted object regardless of soft activity, examples:
    - Reconstructed mass M
    - N-subjettiness ratio $\tau_{32} = \tau_3/\tau_2$
        - N-subjettiness = "χ^2"-like likelihood of jet having N sub-axes

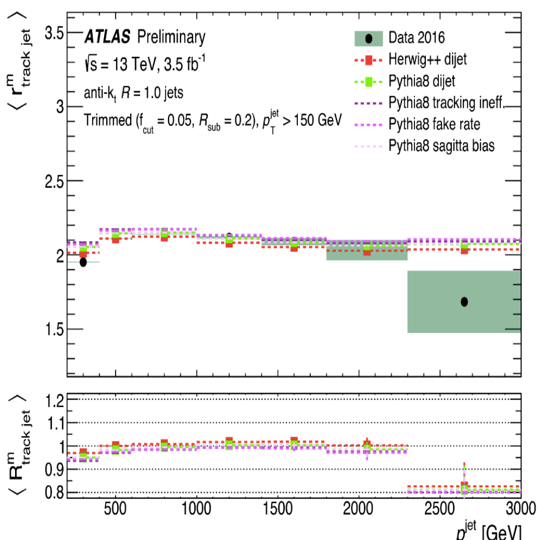


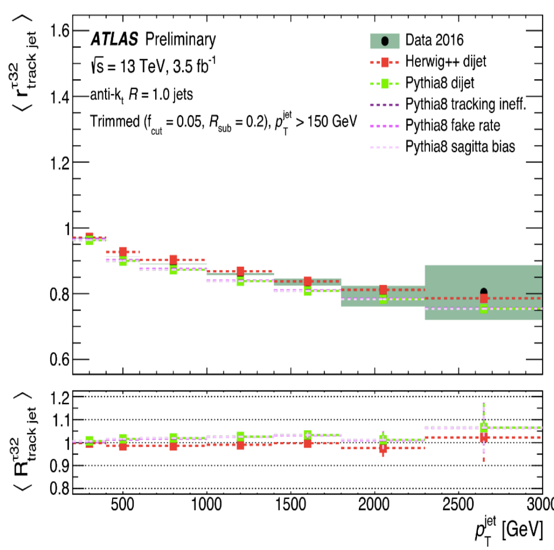
$$\tau_N = \frac{1}{d_0} \sum_k p_{\mathrm{T}k} \times \min(\delta R_{1k}, \delta R_{2k}, ..., \delta R_{Nk}) \ , \quad \text{with} \quad d_0 \equiv \sum_k p_{\mathrm{T}k} \times R$$

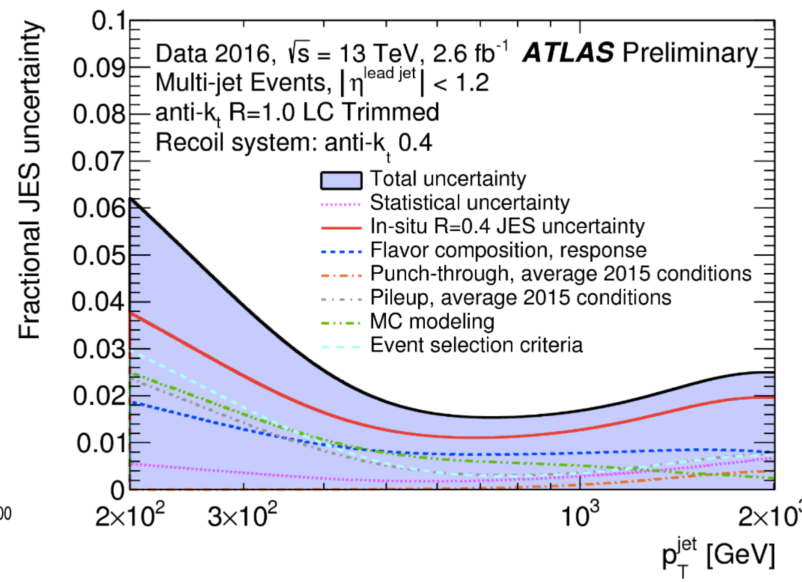
Large-R jet calibration

- Simplified calibration procedure compared to small-R jets
  - No pileup subtraction before calibration
  - Simulation based energy and mass calibration
  - In situ calibration of jet p_T using multi-jet balance
- Validation in data via double ratios
  - jet moment over that from associated tracks
  - Data over simulation



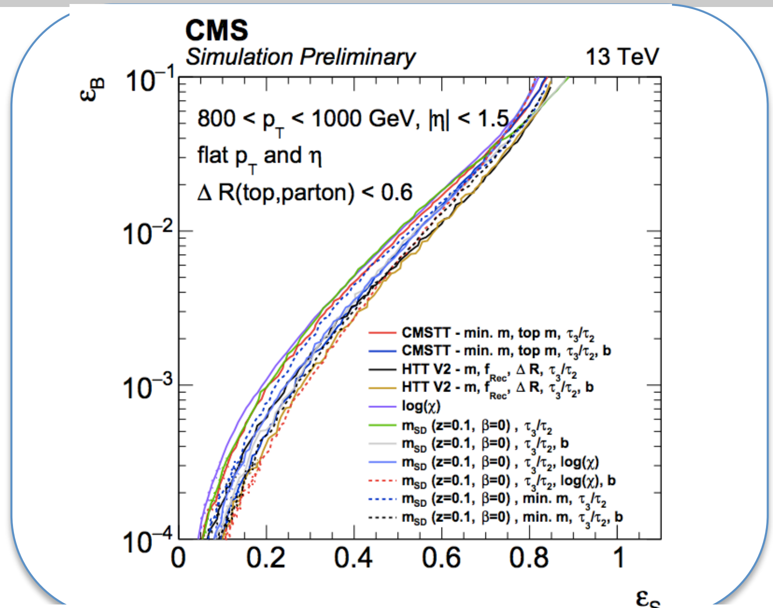


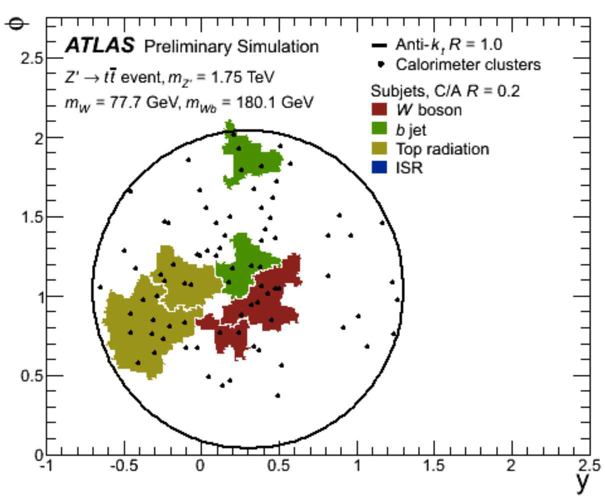


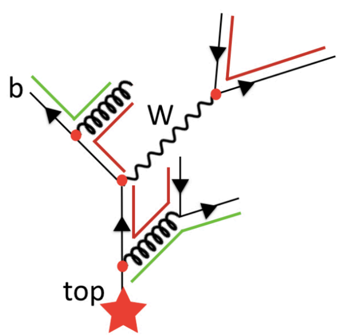


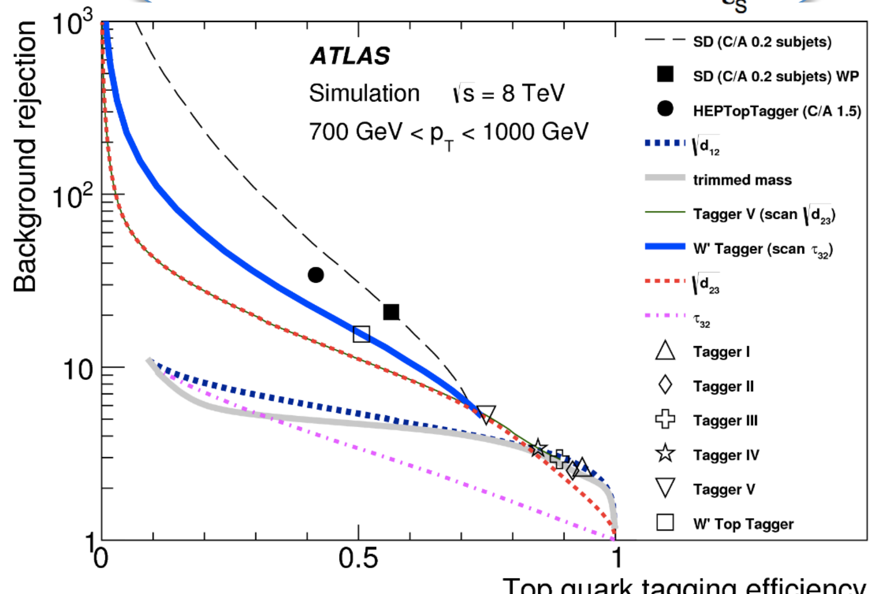
Top tagging

- Both ATLAS and CMS have commissioned and compared a number of top taggers in Run-1
  - Substructure variable taggers based on combinations of mass, τ_{32}, splitting scale, …
  - Shower deconstruction
  - HEPTopTagger
- In general CMS has larger flexibility in studying taggers due to particle flow input objects
  - E.g. variable-R subjets in ATLAS require dedicated calibrations









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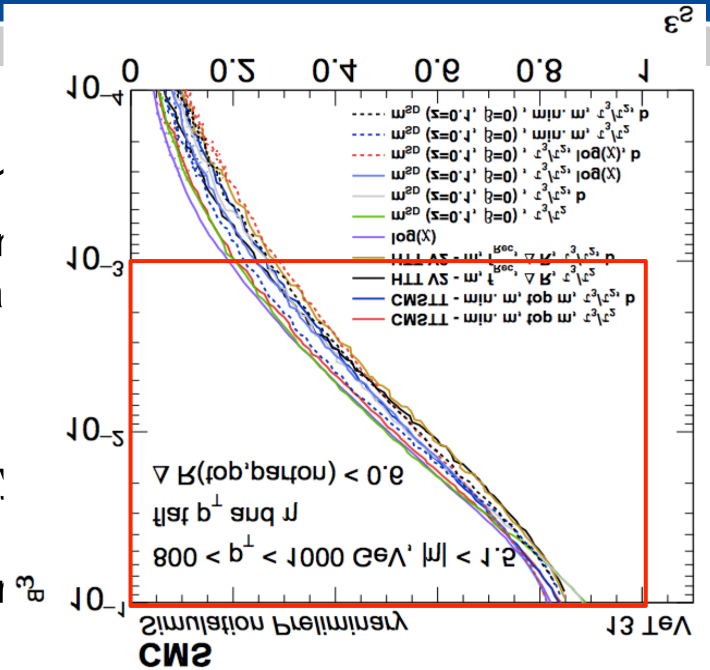
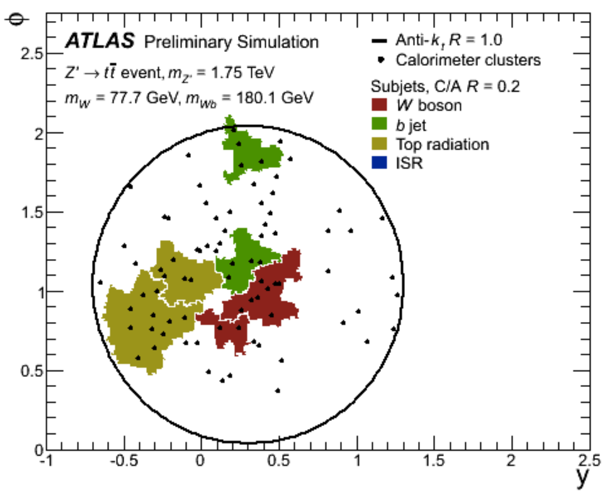
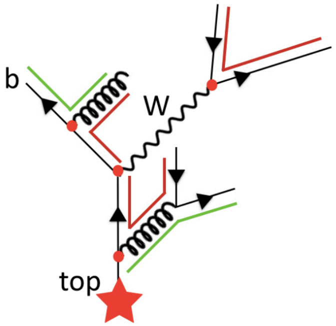
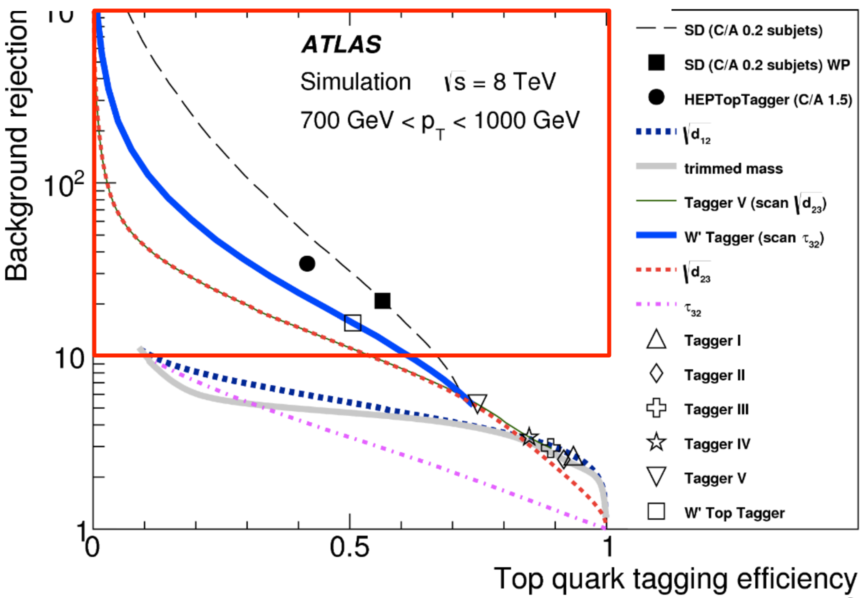
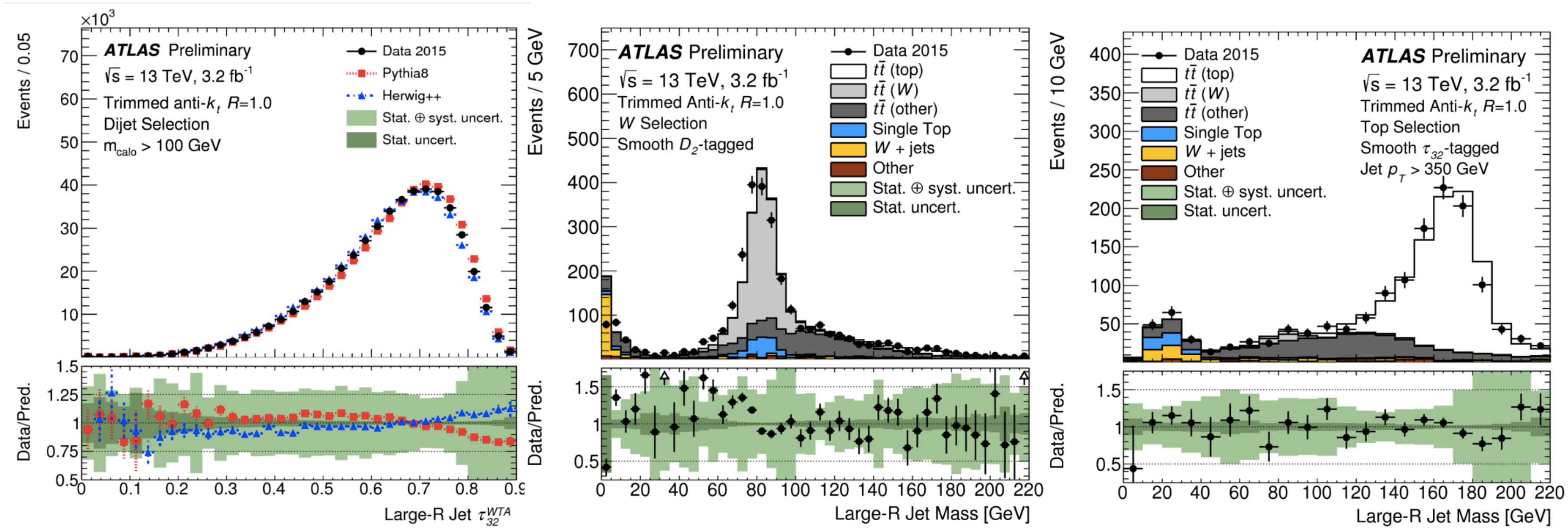








Jet substructure validation in Run-2



- First studies indicate **good agreement** of the performance of substructure variables and boson/top tagging in data and simulated events

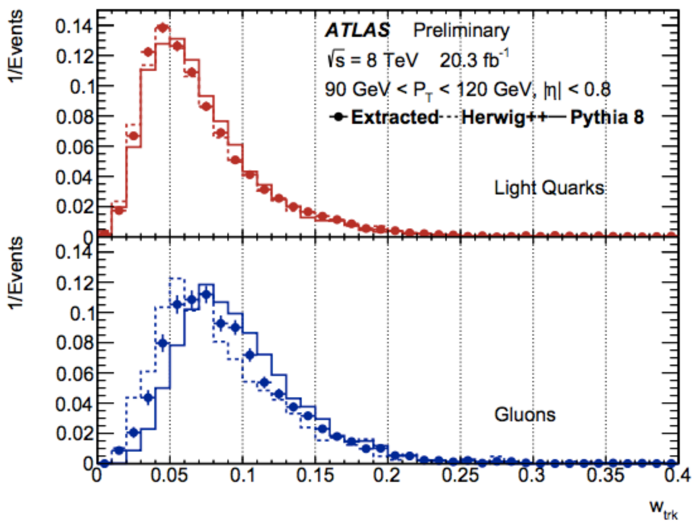
- Variables and taggers largely commissioned and already used in physics analyses
- Detailed performance studies ongoing
  - Both on ATLAS and CMS side

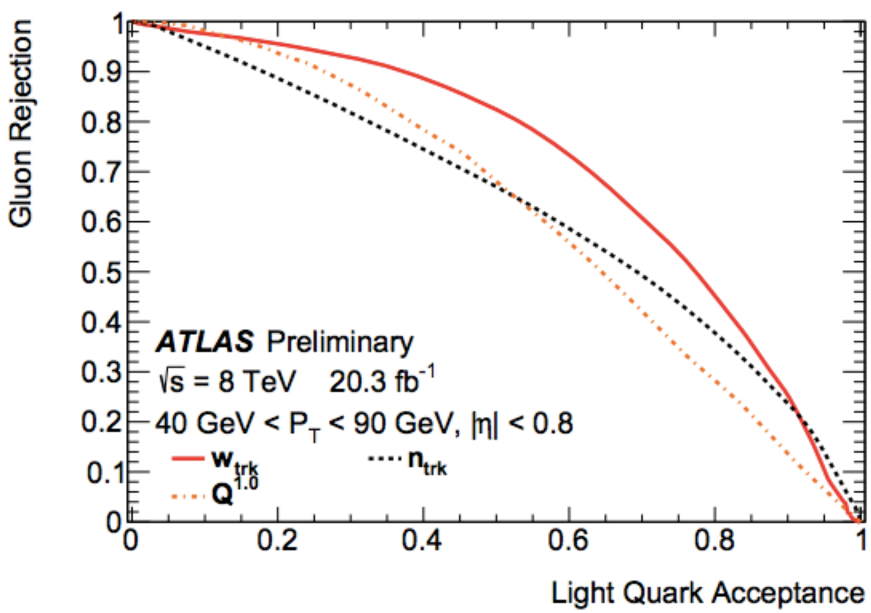
ATLAS Quark-Gluon Tagging

- Quark-gluon tagging uses variables derived from the tracks associated to jets, e.g.
  - number of tracks, p_T or E_T weighted track width, jet charge

  in addition to calorimeter derived variables

- Templates are extracted from data samples of dijet, gamma+jet and Z+jet events
  - Assumption of quark and gluon composition of these samples relies on simulated events

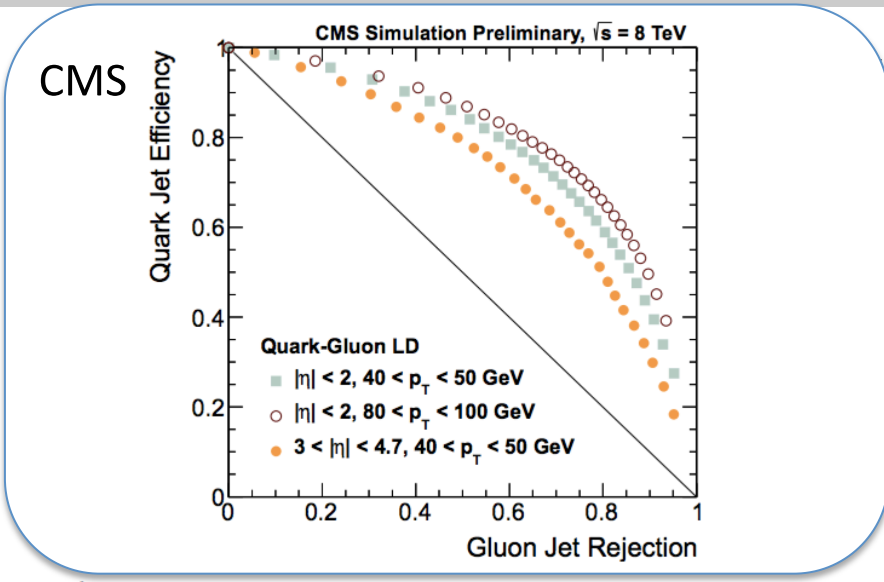


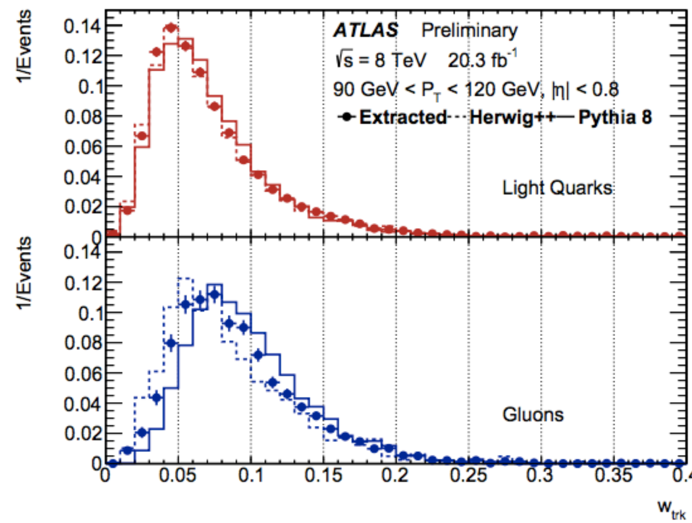


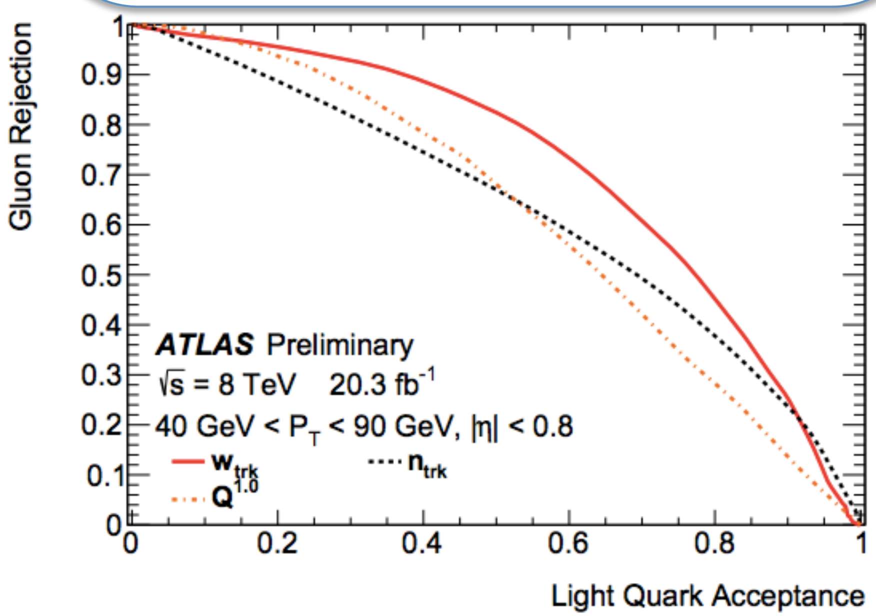
- Uncertainty on gluon expectations from simulation is one of the limiting factors
- Unfolding the discriminating variables for use in generator tuning would benefit their use

Quark-Gluon Tagging

- CMS … rom the tracks associated to jets, e.g. … width, jet charge
- … f dijet, … ion of …







- Uncertainty on gluon expectations from simulation is one of the limiting factors
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Summary and Conclusions

- The LHC, ATLAS and CMS are performing well, currently about $30fb^{-1}$ of proton-proton data at 13 TeV recorded

- Jets are fundamental objects for physics analysis at the LHC, despite not being ‘fundamental objects’
- Even if not signal, often an important source of systematic uncertainties

- Huge effort in ATLAS and CMS goes into reconstructing, calibrating and commissioning jet objects
  - Performance of small-R jets well under control, despite challenging pileup conditions
    - Improvements still expected, as well as new approaches, e.g. particle flow at ATLAS
  - Treatment and use of large-R jets shows large variety
    - Significant amount of development and studies still ongoing

Thanks for your attention!

Backup

ATLAS - Track-assisted large-R jets

- If one trusts quantities derived from associated tracks for validation, why not directly use them?
  - Track assisted mass TA

$$m^{\mathrm{TA}} = \frac{p_{\mathrm{T}}^{\mathrm{calo}}}{p_{\mathrm{T}}^{\mathrm{track}}} \times m^{\mathrm{track}}$$

- Performance is mixed when done on fat jet level, apply on subjets -> TAS
  - Alternative: Linear combination with cluster based mass