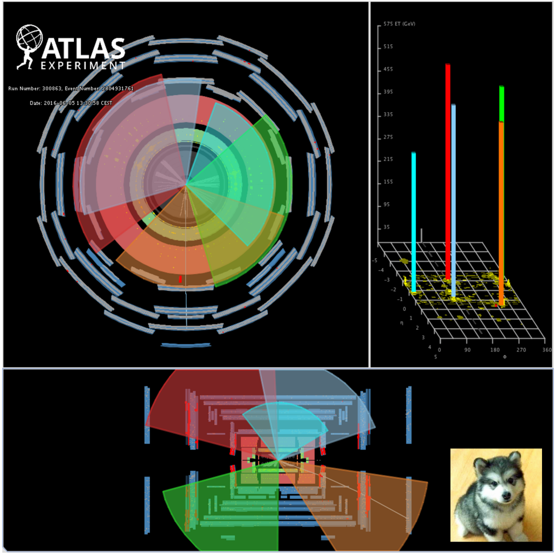
Reconstruction of large-R jets and in-situ techniques for their calibration

Ayana T. Arce [Duke University]
on behalf of the ATLAS Collaboration

designed to **accurately+precisely reconstruct p^{μ} of hadronically decaying particle**,

to **not distort characteristic properties of** q/g-initiated jets,

and to **preserve sufficient detail about hadronic decay + parton shower**.



Challenges for large-radius jet reconstruction

designed to **accurately+precisely reconstruct p^{μ} of hadronically decaying particle**,

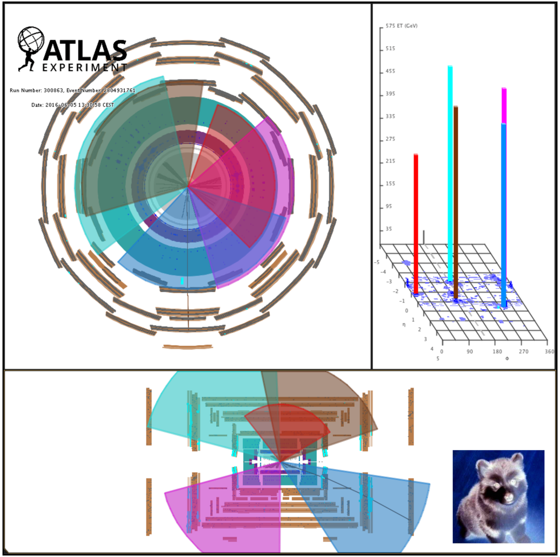
but “standard candles” are rare

to **not distort characteristic properties of** q/g-initiated jets,

large areas are more sensitive to pileup

and to **preserve sufficient detail about hadronic decay + parton shower**.

and we’re forced to search at fine angular scales



ATLAS EXPERIMENT

Large radius jet p^μ is well-modeled and precisely measured[1] by ATLAS from $p_T \sim$ 0.1 to several TeV.

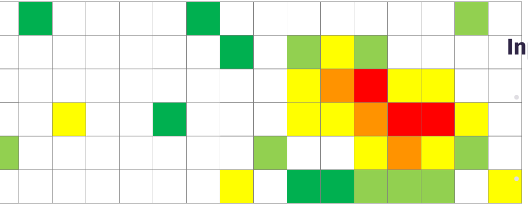
residual energy scale	known to 1-2 %
residual jet mass scale	known to 2-10 %
resolution of p_T and mass measurements	known to better than 15 %

How? CERN-EP-2018-191

Measure distributions of jet kinematics and ratios of jet kinematic quantities to *references* in data and simulation.

- broad p_T coverage achieved using high-statistics processes (q/g-initiated jets);
- necessary m coverage comes from enriched samples of W- and t-initiated jets.

[1] for central, large-R jets with simulation and in-situ calibration sequence applied. residual scales refer to the ratio of the absolute scales in collision data and simulation, while absolute scales are relative to stable-particle level jets. your boost may vary.

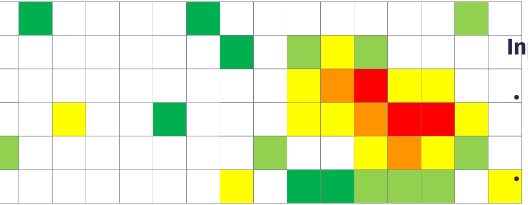


Input : topological clusters calibrated to hadronic scale

- Topoclusters (Chris's talk) corrected for non-compensation, threshold effects, dead material by weighting cell signals
- **LCW calibration** bases cell weights on cluster classification (spectrum from *totally EM* (π^0) to hadronic ($\pi^\pm$))

Algorithm : Anti-k_T (R=1.0) jet building + trimmming

- uses massless topocluster four-vectors, relative to primary vertex
- jet constituents are then clustered with k_T (R=0.2); soft (less than 5% of jet p_T) subjets are removed.



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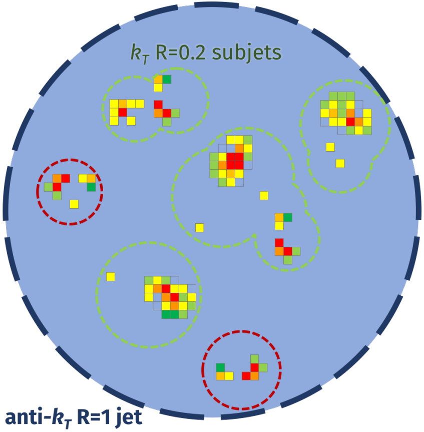

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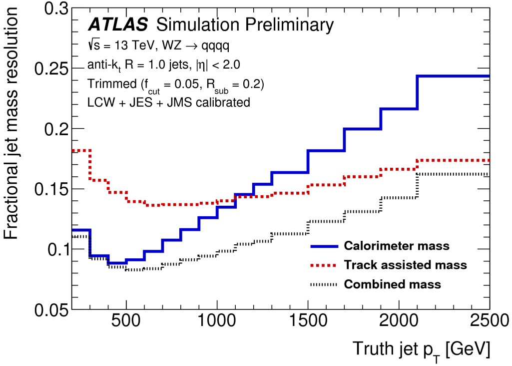
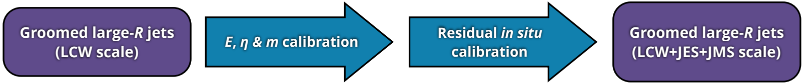
- **calorimeter mass** resolution degrades at high p_T because of cluster and calo shower size
- **track-assisted mass** : use fine tracker granularity
  - $m_{TA} = m_{\text{track}} \times \frac{p_{T\,\text{calo}}}{p_{T\,\text{track}}}$
- **Combined mass** is resolution-weighted combination:

$$w_{\text{det}} = (\sigma[m_{\text{det}}])^{-2}$$

$$m_{\text{comb}} = \left(\sum_{\text{TA,calo}} w_{\text{det}} m_{\text{det}}\right) / \left(\sum_{\text{TA,calo}} w_{\text{det}}\right)$$

JETM-2017-002





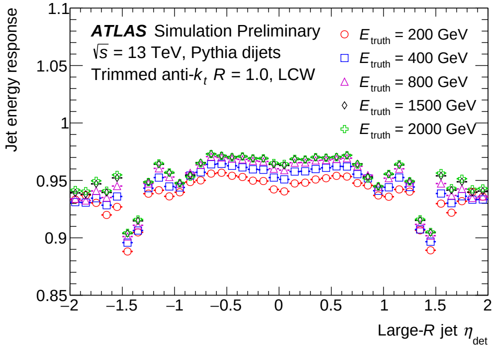
A correction to the jet energy, pseudorapidity and mass is derived from MC to bring the reconstructed jet to the particle jet scale.

Residual correction determined using *in situ* measurements to bring data in agreement with MC. Applied only to data.

Measurements to quantify and/or correct for:

- differences in reconstructing and trimming jets at reconstructed vs. stable particle level
- relative differences in response in different regions of ATLAS calorimeter and simulated calorimeter
- absolute energy and mass scales

Jet energy scale

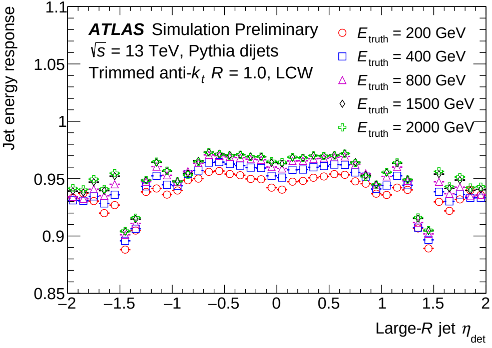


Determine average, expected detector effects in bins of (p_T, η_{det})

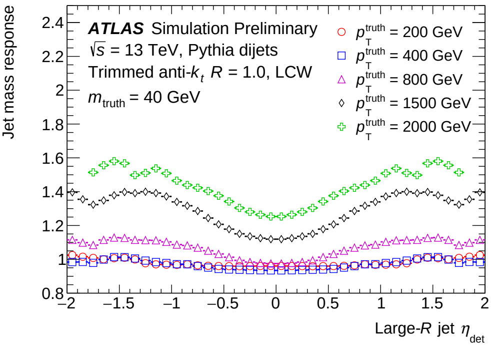
Response is the ratio of *reconstructed* to *particle-level*

$E = E_0 \times c_{\text{JES}}$ $\quad \eta = \eta_0 + \Delta\eta$ $\quad m = m_0 \times c_{\text{JES}}$

Jet energy scale

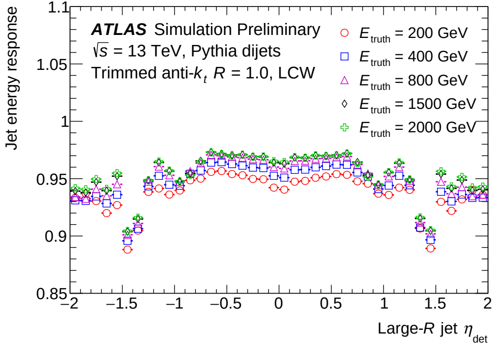


Jet (calorimeter) mass scale



$E = E_0 \times c_{JES}$ $\quad \eta = \eta_0 + \Delta\eta$ $\quad m = m_0 \times c_{JES} \times c_{JMS}$

Jet energy scale



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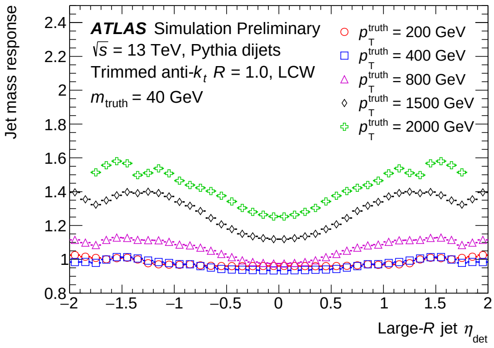
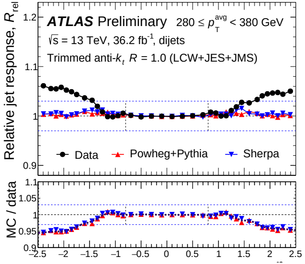
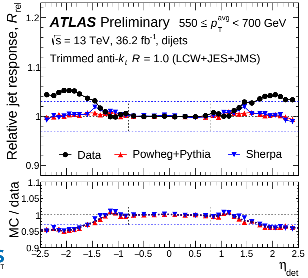


$$E = E_0 \times c_{JES} \qquad \eta = \eta_0 + \Delta\eta \qquad m = m_0 \times c_{JES} \times c_{JMS} \qquad p_T = c_{JES}\sqrt{E_0^2 - c_{JMS}^2\, m_0^2}\cosh\left(\eta_0 + \Delta\eta\right)$$



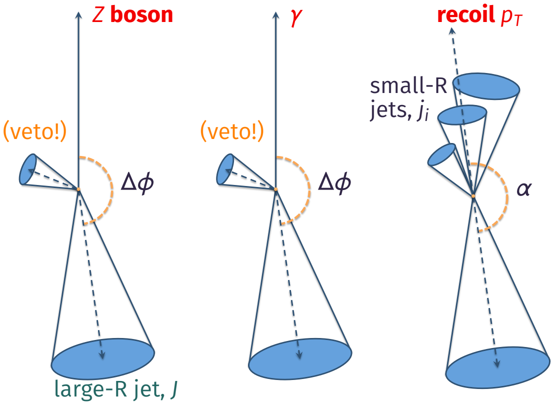


Correct for the average p_T asymmetry between central, *reference* jets and forward, *probe* jets as a function of η_{det}^{probe}.

- Select dijet topology:
  - two jets with $\Delta\phi > 2.5$,
  - vetoing additional high p_T jets (more than 20 % of $p_T^{j1} + p_T^{j2}$)

The average of the asymmetry, $\mathcal{A} = 2\frac{p_T^{fwd} - p_T^{central}}{p_T^{fwd} + p_T^{central}}$, provides a relative scale:

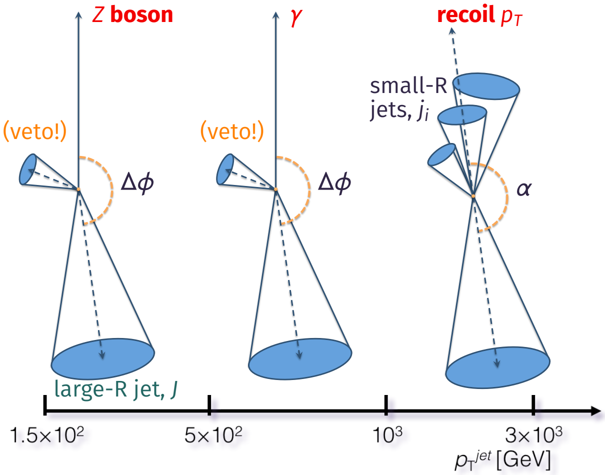
$$R_{rel} = \frac{2 + \langle\mathcal{A}\rangle}{2 - \langle\mathcal{A}\rangle}$$



Which reference object(s) to use?

Relevance of a calibration reference depends on its:

- energy scale uncertainty
- trigger rate and purity
- production cross-section



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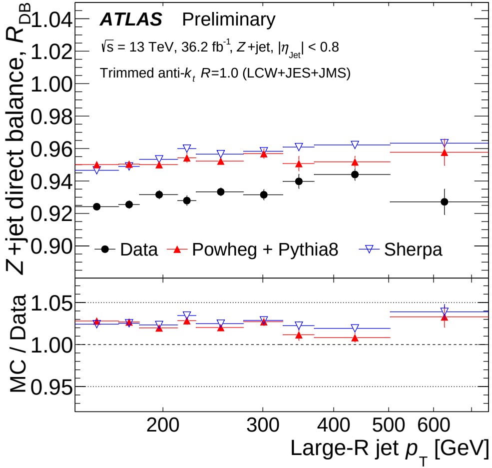
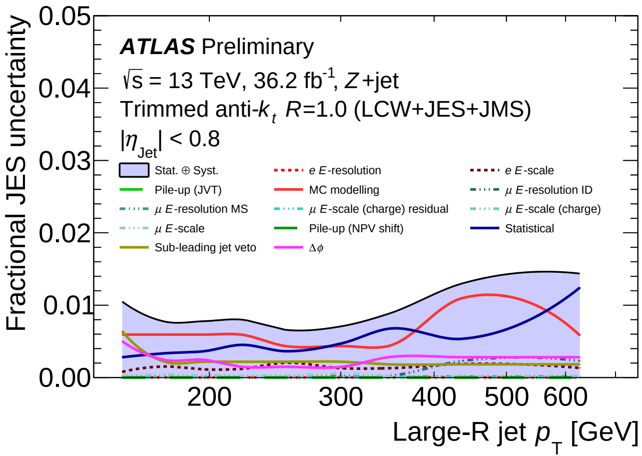


Z^0/γ direct balance

Require jet to recoil against well-measured reference:

- $p_T^{ref} = p_T^{\gamma/Z^0} \cos\Delta(\phi)$
- $\Delta(\phi) \sim \pi$, with veto on extra (R=0.4) jets, unless $p_T^j \ll p_T^{ref}$



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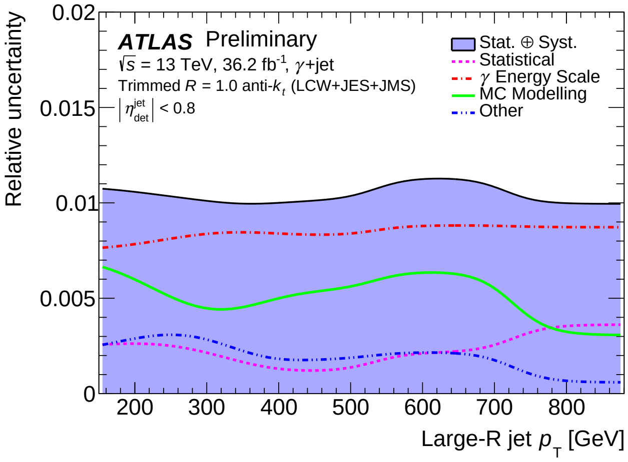
- $Z \rightarrow \ell\ell$ + jet limited by small production rate above $p_T \sim 500$ GeV

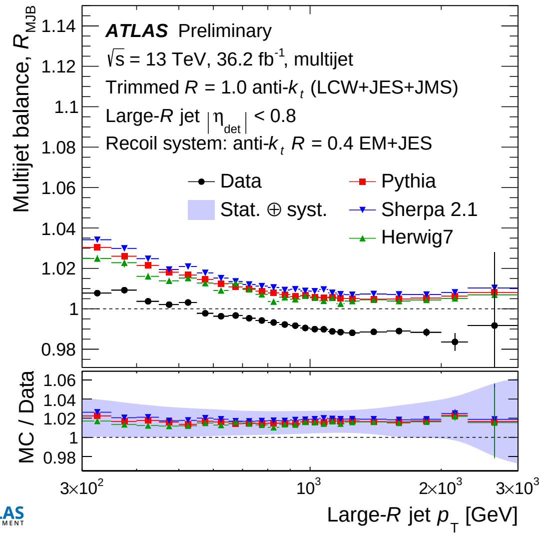


Photon direct balance

Require jet to recoil against well-measured reference:

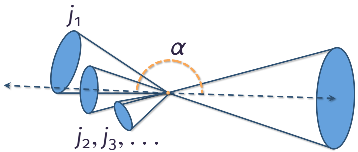
- $p_T^{\text{ref}} = p_T^{\gamma/Z^0} \cos\Delta(\phi)$
- $\Delta(\phi) \sim \pi$, with veto on extra (R=0.4) jets, unless $p_T^j \ll p_T^{\text{ref}}$
- For γ + jet, the photon energy scale uncertainty contributes significantly (Matt's poster)

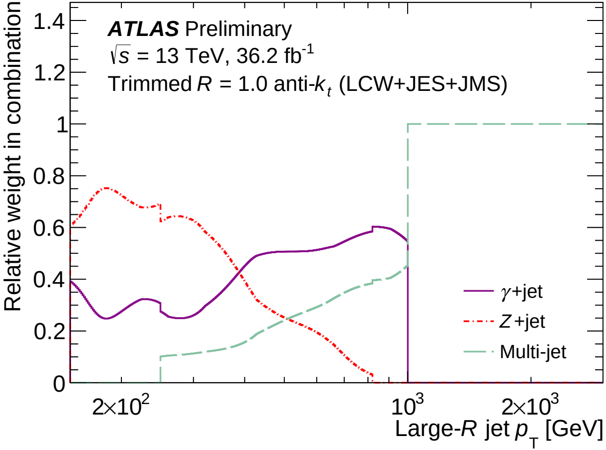
COMPARE THE EXPECTED SCALE (FROM SIMULATION) TO THAT OF DATA



Multijet balance

- reference: a recoiling system of *many, calibrated* small-R jets ($|\alpha - \pi| < 0.3$)
- reject dijet topology ($p_T^{j_1} < 0.8 \sum_i p_T^{j_i}$)



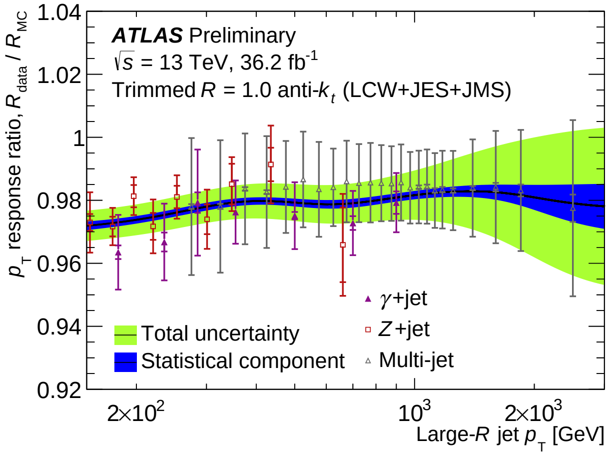


Combination

Weights for each measurement are derived by χ^2 minimization using statistical and systematic uncertainties of finely-binned scale measurements (interpolated with splines), and accounting for all correlations.

Residual energy scale measurement from $p_T \in 0.2 - 3$ TeV

Compare the expected scale (from simulation) to that of data



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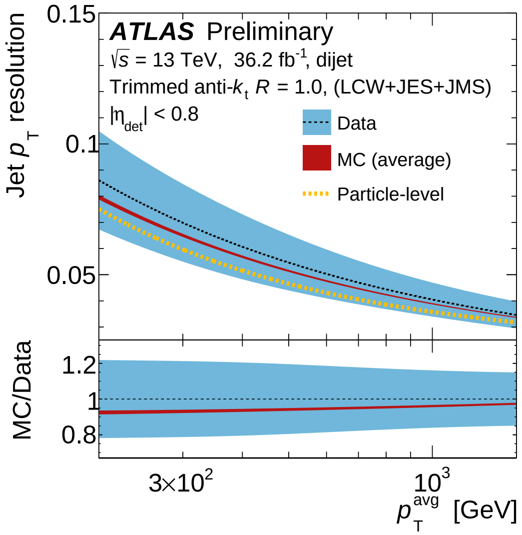
THE UNCERTAINTY ON THE THE JET ENERGY RESOLUTION *JER* IN DATA IS IMPORTANT FOR SEARCHES.

The width of the observed $\mathcal{A} = 2\frac{p_T^{\mathrm{probe}} - p_T^{\mathrm{ref}}}{p_T^{\mathrm{probe}} + p_T^{\mathrm{ref}}}$ distribution can be explained as

$\sigma_A^2 = \sigma_{A,truth}^2 + \sigma_{A,det}^2$.

- for central, dijet events (in which probe and reference are interchangeable)

$$JER \equiv \left(\frac{\sigma[p_T]}{p_T}\right) = \sigma_{A,det}/\sqrt{2}$$



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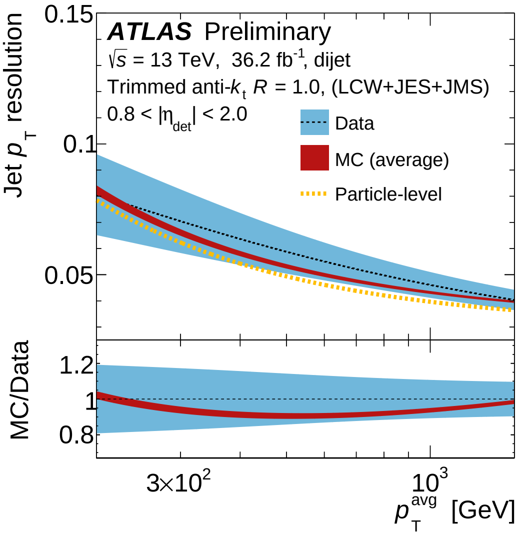
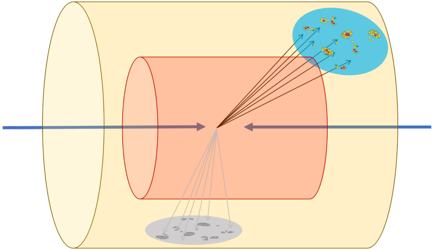
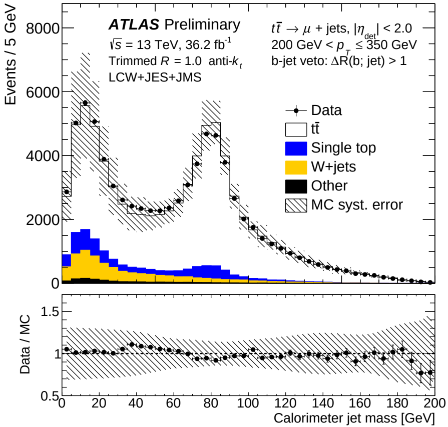


Comparing track-jets (R_{trk} scale)



"Folding" $W^{\pm}$, t jet simulation (scale, resolution)



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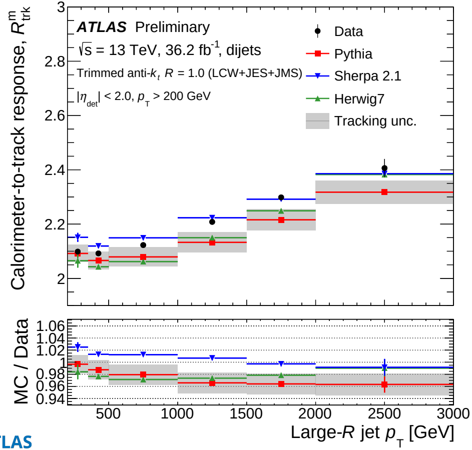

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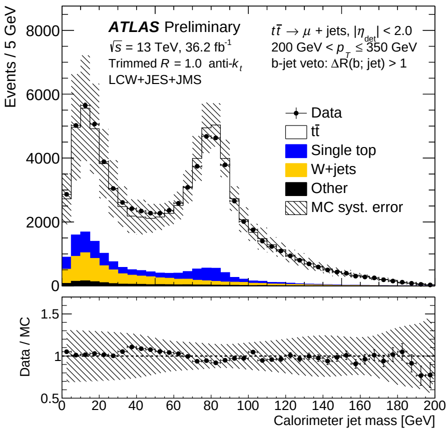
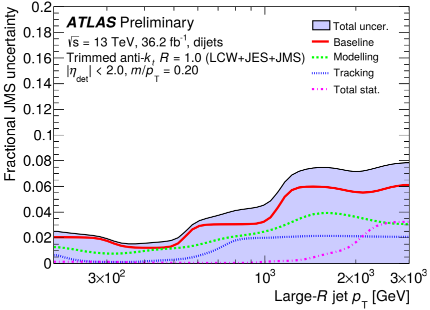
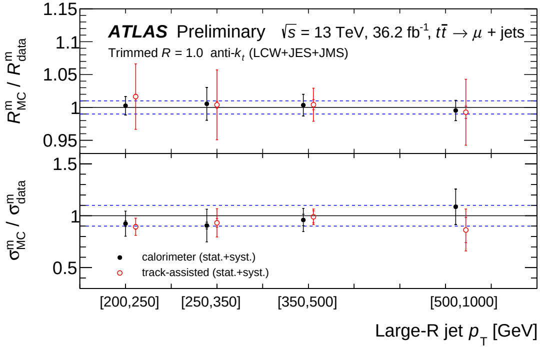


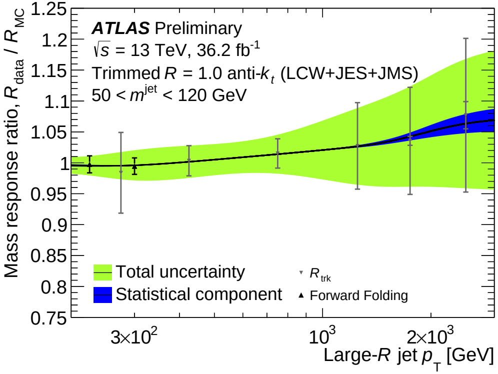
ATLAS EXPERIMENT

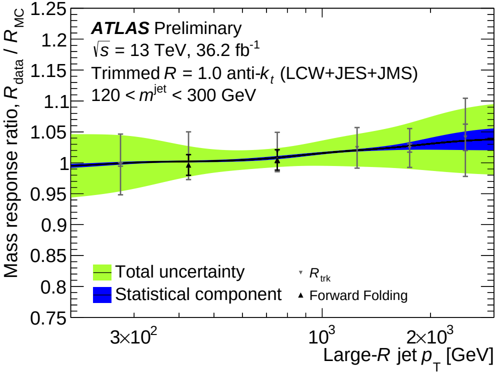
R_{trk} constrains JMS uncertainty



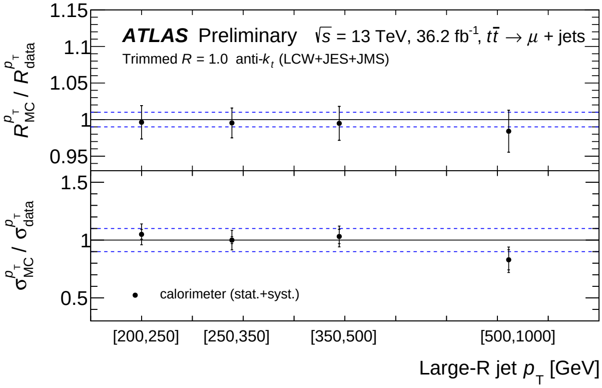
Forward-folding measures JMS and JMR for calo/TA jets




ATLAS Preliminary
√s = 13 TeV, 36.2 fb-1
Trimmed R = 1.0 anti-kt (LCW+JES+JMS)
50 < mjet < 120 GeV
Total uncertainty
Statistical component
Rtrk
Forward Folding
Mass response ratio, Rdata / RMC
Large-R jet pT [GeV]
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
3×10^2
10^3
2×10^3

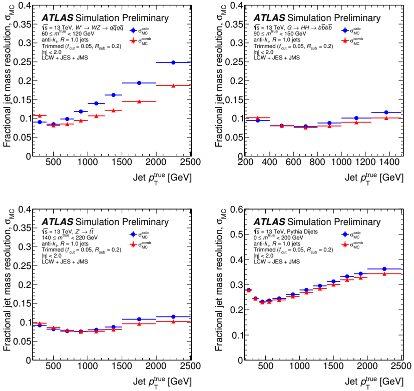

ATLAS Preliminary
√s = 13 TeV, 36.2 fb-1
Trimmed R = 1.0 anti-kt (LCW+JES+JMS)
120 < mjet < 300 GeV
Total uncertainty
Statistical component
Rtrk
Forward Folding
Mass response ratio, Rdata / RMC
Large-R jet pT [GeV]
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
3×10^2
10^3
2×10^3

t and W jet p_T after in-situ energy calibration

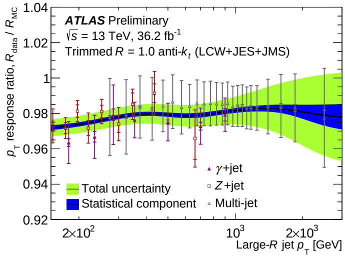


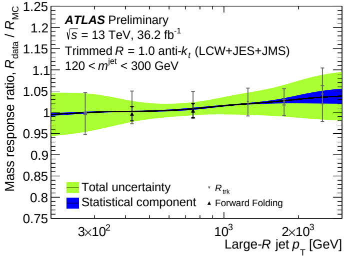
Jet mass performance for t, W, H and q/g

ATL-PHYS-PUB-2018-015



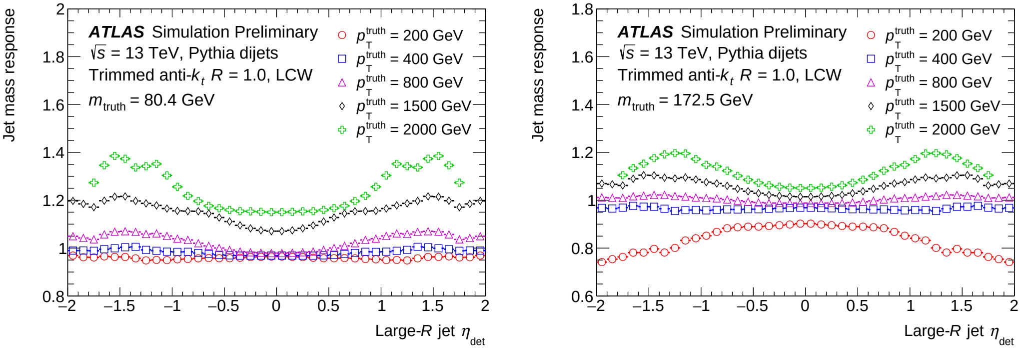
- ATLAS large-R jet reconstruction and calibration chain lead to **precise** jet energy measurements, enabling resolution studies, tagger development, and more.
  - A residual energy calibration based on light jets yields **well-calibrated energies, masses, and resolutions for massive hadronic decays**
- JER is well-modeled and already well-constrained
- JMR is improved with combined mass, well-measured in data

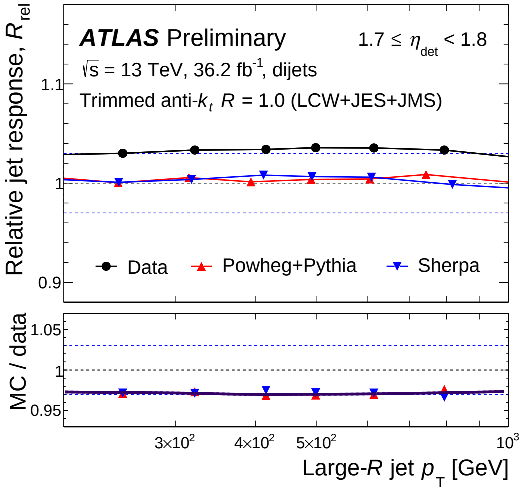


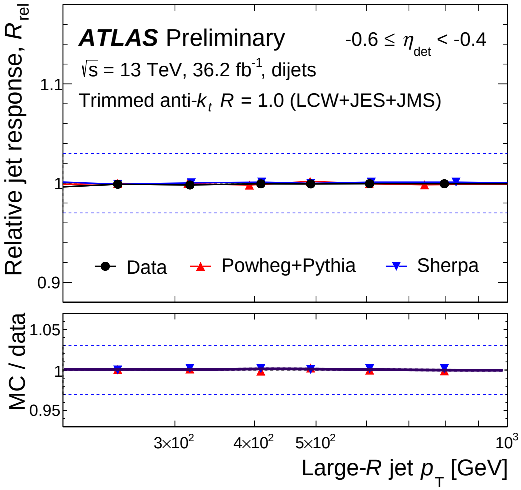


Backup

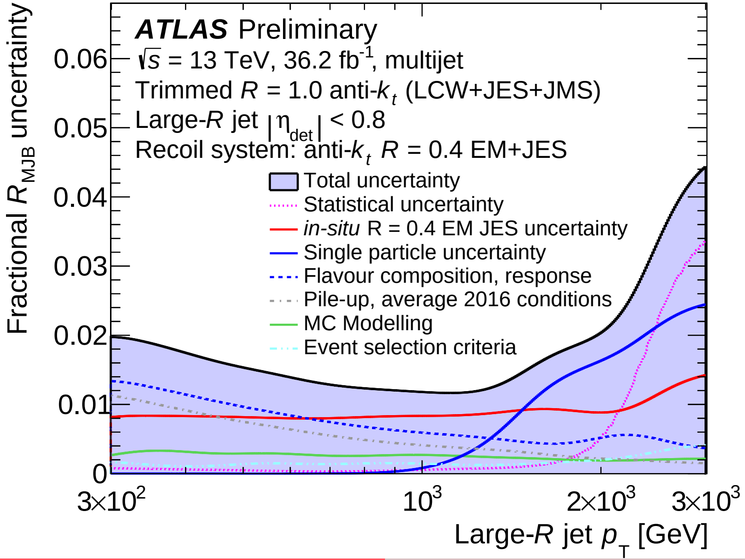
Monte Carlo	calibrates E, η then m:	$E_{\mathrm{MC}} = c_{\mathrm{JES}}\, E_{\mathrm{O}},\, m_{MC} = c_{\mathrm{JMS}}\, c_{\mathrm{JES}}\, m_{\mathrm{O}}$
		$(p_T)_{\mathrm{MC}} = c_{\mathrm{JES}} \sqrt{E_{\mathrm{O}}^2 - (c_{\mathrm{JMS}} m_{\mathrm{O}})^2} \cosh\left(\eta + \Delta\eta\right)$
In-situ	measures p_T then m :	$E = c_s \sqrt{E_{\mathrm{MC}}^2 + (c_m^2 - 1) m_{\mathrm{MC}}^2},\; m = c_m\, c_s m_{\mathrm{MC}}$
		$p_T = c_s\, (p_T)_{\mathrm{MC}}$


ATLAS Simulation Preliminary
√s = 13 TeV, Pythia dijets
Trimmed anti-k_t R = 1.0, LCW
m_truth = 80.4 GeV
p_T^truth = 200 GeV
p_T^truth = 400 GeV
p_T^truth = 800 GeV
p_T^truth = 1500 GeV
p_T^truth = 2000 GeV
Jet mass response
Large-R jet η_det
ATLAS Simulation Preliminary
√s = 13 TeV, Pythia dijets
Trimmed anti-k_t R = 1.0, LCW
m_truth = 172.5 GeV
p_T^truth = 200 GeV
p_T^truth = 400 GeV
p_T^truth = 800 GeV
p_T^truth = 1500 GeV
p_T^truth = 2000 GeV
Jet mass response
Large-R jet η_det





ATLAS EXPERIMENT

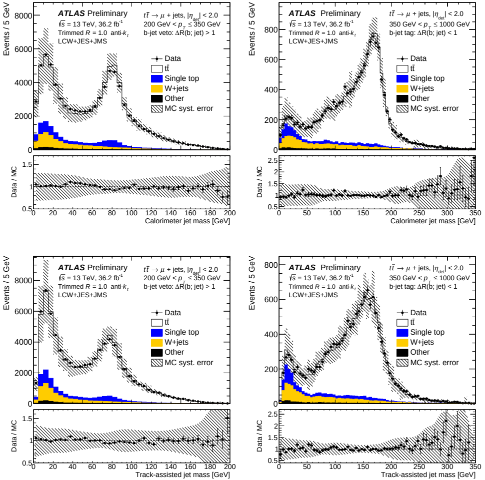

ATLAS Preliminary
√s = 13 TeV, 36.2 fb-1, multijet
Trimmed R = 1.0 anti-kt (LCW+JES+JMS)
Large-R jet |ηdet| < 0.8
Recoil system: anti-kt R = 0.4 EM+JES
Total uncertainty
Statistical uncertainty
in-situ R = 0.4 EM JES uncertainty
Single particle uncertainty
Flavour composition, response
Pile-up, average 2016 conditions
MC Modelling
Event selection criteria
Fractional R_MJB uncertainty
0
0.01
0.02
0.03
0.04
0.05
0.06
3×10^2
10^3
2×10^3
3×10^3
Large-R jet pT [GeV]

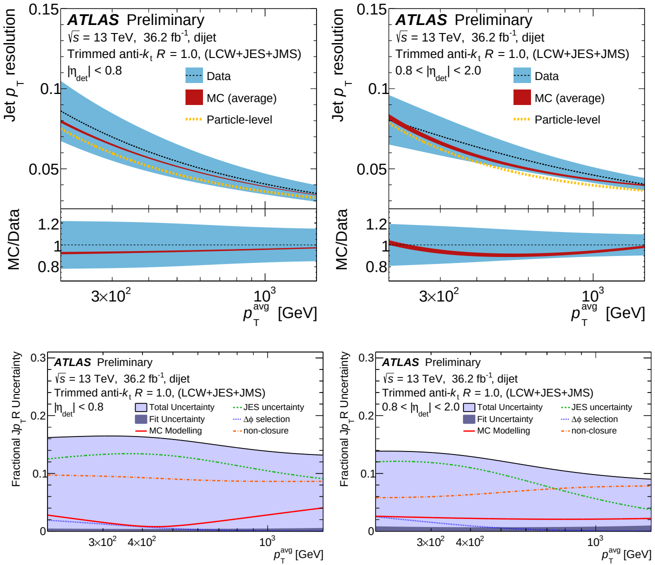
Forward folding event selection: 25 GeV muon trigger

- Leptonic top decay:
  - tight, isolated ($\Delta R_{\mu,\mathrm{jet}} > 0.4$) muon
  - Missing $E_T > 20$ GeV; $m_\mathrm{T} > 60$ GeV
  - At least one small-R jet: $p_T > 25$ GeV and $\Delta R(j, \mu) < 1.5$
- Opposite side hadronic decay: $p_{T_J} > 200$, $\Delta R_{\mathrm{j,J}} > 2$
  - top jet $(p_T > 350)$ GeV or
  - W jet $(p_T < 350)$ GeV
- At least one b-tagged jet
  - $\Delta R_{b,\mathrm{J}} < 1$ *confirms* top jet or *vetoes* W jet.

ATLAS EXPERIMENT

FORWARD FOLDING




ATLAS Preliminary
√s = 13 TeV, 36.2 fb-1, dijet
Trimmed anti-kt R = 1.0, (LCW+JES+JMS)
|ηdet| < 0.8
0.8 < |ηdet| < 2.0
Data
MC (average)
Particle-level
Jet pT resolution
MC/Data
pTavg [GeV]
Fractional JpTR Uncertainty
Total Uncertainty
Fit Uncertainty
MC Modelling
JES uncertainty
Δϕ selection
non-closure

ATL-PHYS-PUB-2018-015