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Jet Energy Scale & Jet Energy Resolution from hadronic W mass in $t\bar{t}$

2512.17482

Adriana Dohnalová
on behalf of the ATLAS Collaboration

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ATLAS
EXPERIMENT

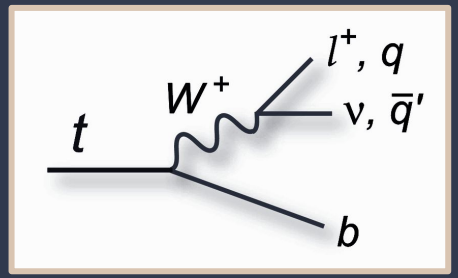
Introduction

JES = mean of the response distribution $p_{T,reco}/p_{T,truth}$

JER = width of the response distribution $p_{T,reco}/p_{T,truth}$

1-lepton $t\bar{t}$ events

- high x-section at the LHC
- clean signature - minimal background:
  - 1 charged lepton
  - 2 b-jets
  - W->qq

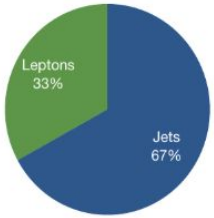


Idea:

W→qq̄ for *in situ* calibration

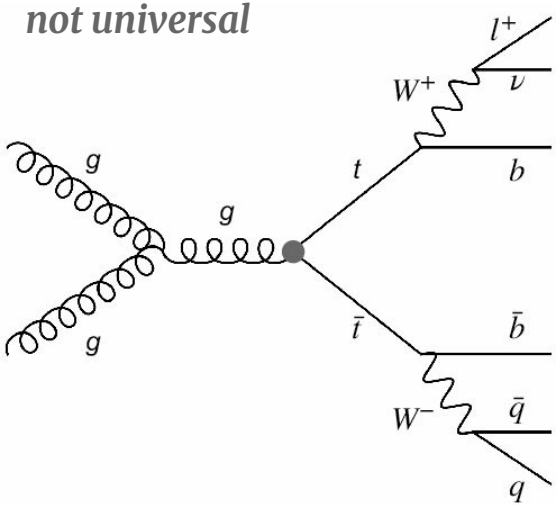
- only used as a cross-check of JES calibration before:
  JES 7 TeV [1406.0076]

W boson decay



several top mass measurements use W mass to constrain the JES uncertainty:
top mass 13 TeV [2502.18216],
top mass 8 TeV [1810.01772],
top mass 7 TeV [1503.05427]

we know it works but the corrections are not universal



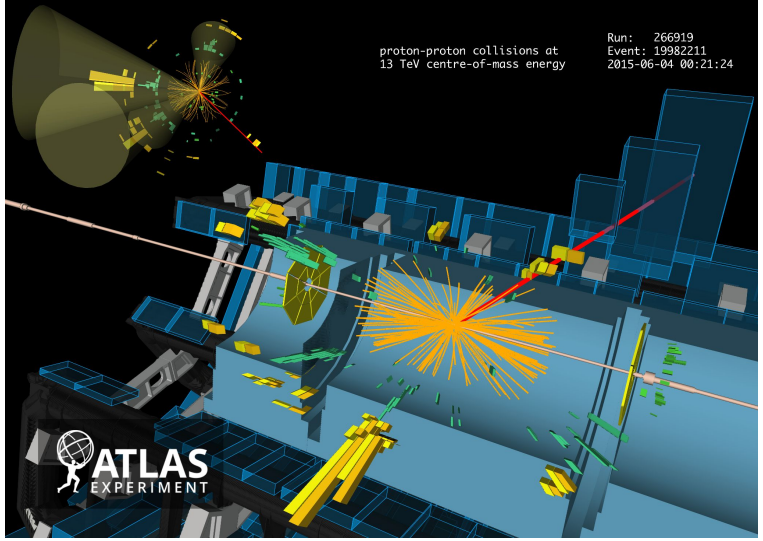
***in situ* calibration** - the last step in jet calibration in ATLAS, uses data to correct residual differences between data and simulation

Analysis strategy

Event selection

- **≥ 4 jets (anti-k_T R = 0.4, PFlow jets)**
- **≥ 2 b-jets** (> 30 GeV)
- **1 electron/muon** (p_T > 27 GeV)
- E_T^{miss} > 30 GeV

- identify jets from W decay against b-jets
- reconstruct **invariant mass of the hadronic W boson** from the jets
  - very sensitive to **JES and JER**
- **Forward-Folding** used to generate **W mass templates** for different JES and JER assumptions
- fit the **mean** of the template distributions to the mean in data and find the optimal **JES**
- and fit **standard deviation** of templates to find optimal **JER**



χ^2 based top-quark reconstruction

- need to identify jets from W decay
- jet permutations are evaluated and the permutation with the best χ^2 is considered the correct one

$$\chi^2 = \frac{(m_{\mathrm{W,reco}} - 80.38)^2}{resolution^2_{m_{\mathrm{W}}}} + \frac{(m_{\mathrm{top,reco}} - 172.5)^2}{resolution^2_{m_{\mathrm{top}}}}$$

- require χ^2 < 1 - best jet permutation selected, otherwise the event is dicarded

Forward-Folding

- all jets folded
- analysis repeated for various assumptions of data-MC disagreement in JES or JER

$$\mathcal{R} = \text{argmax}\left\{ \frac{p_{\mathrm{T}}^{\mathrm{reco}}}{p_{\mathrm{T}}^{\mathrm{truth}}} \right\}$$

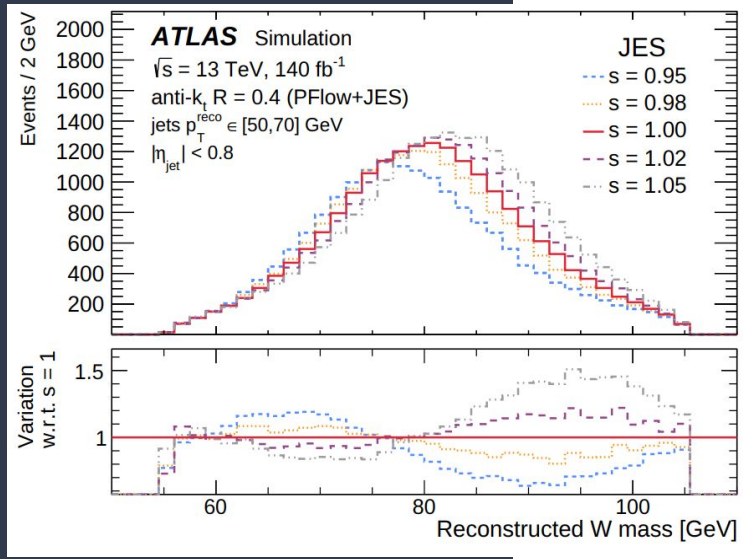
the mode of the jet response distribution - binned in jet p_T, $|\eta|$ and flavour

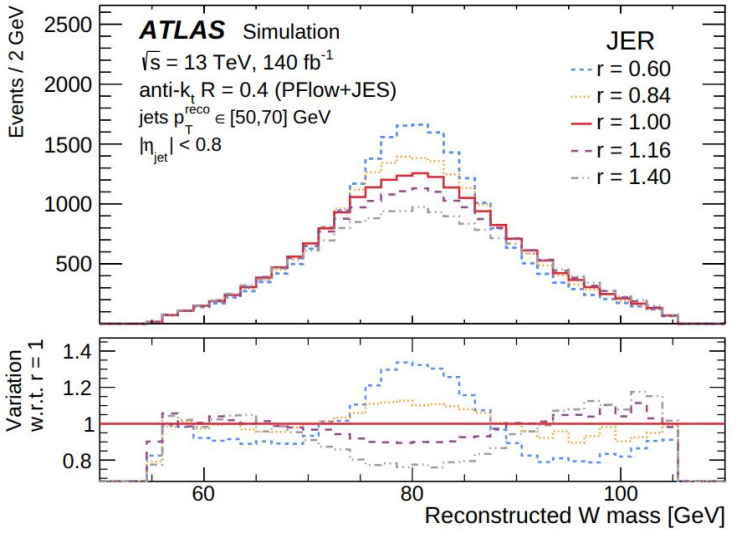
$$p_{\mathrm{T}}^{\mathrm{folded}} = s \cdot p_{\mathrm{T}}^{\mathrm{reco}} + \left(p_{\mathrm{T}}^{\mathrm{reco}} - \mathcal{R} \cdot p_{\mathrm{T}}^{\mathrm{truth}} \right) \cdot (r - s)$$

reconstruct W mass from the “folded” jets:

W mass templates with different assumptions of JES (s) or JER (r):

JES variation = shift of the peak

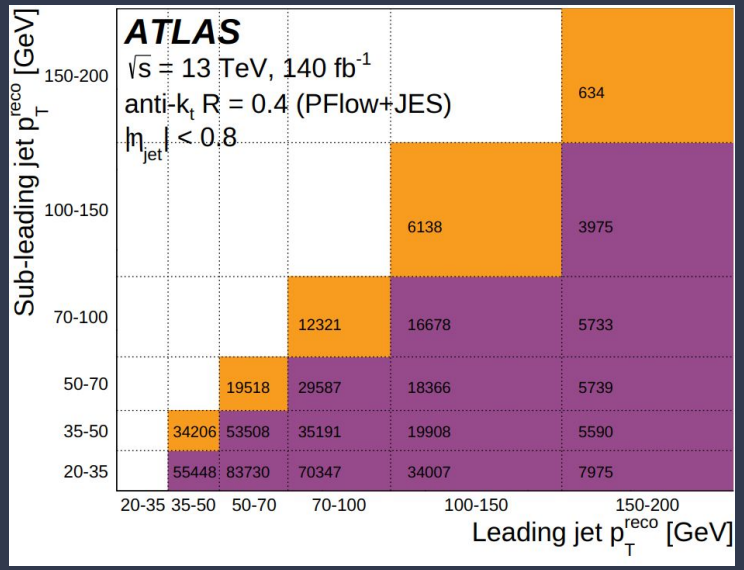




JER variation = change of width

Analysis regions

defined by p_T and $|\eta|$ of the jets from W



- ***diagonal regions***
  both jets from W from the same p_T bin

  - templates in *s* ranging from 0.95 to 1.05 - one scale assumption for both jets

  - templates in r ranging from 0.6 to 1.4 - one resolution assumption for both jets

  11 JES templates + 11 JER templates

- ***off-diagonal regions***
  each jet from W from different p_T bin

  - templates in s_1 and s_2- one scale (resolution) assumption for the leading jet and another for the subleading jet

  - templates in r_1 and r_2 - one resolution assumption for the leading jet and another for the subleading jet

  121 JES templates + 121 JER templates

JES/JER extraction

- in each region: parametrise the mean/STDEV of W mass distribution as a function of s(JES)/r(JER)
- the likelihood will be the product of Gaussians over regions

$$\mathcal{L}(\vec{\mu}|\vec{s}) = \prod_{i \in \text{reg}} G[\mu_i | \mathcal{F}_i(\vec{s}), \sigma_{\mu_i}]$$

$\vec{\mu}$ mean (STDEV) values measured in data

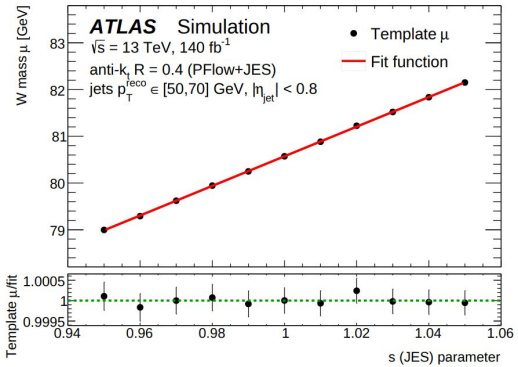
$\vec{s}$ scale (resolution) parameters to be estimated

$\mathcal{F}$ parametrisation formula

σ_{μ_i} uncertainty on the mean (STDEV) values in region i

JER uncertainties considered for JES measurement and vice versa

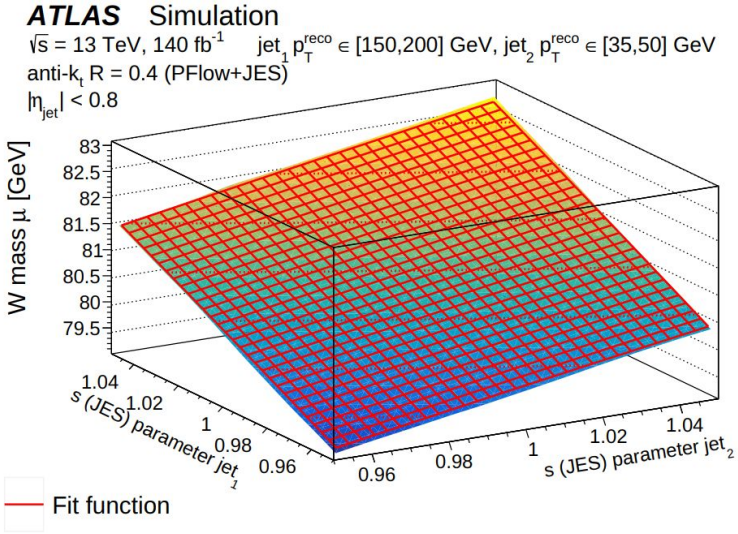
Example parametrisation (for JES)



1D parameterization for **diagonal regions**

Linear dependence shows how strongly W mass correlates with JES

2D parameterization for **off-diagonal regions**



Results

- Run 2 corrections are consistent with what is obtained with standard methods
- Run 3 JES corrections closer to 1 than Run 2 corrections - suggests better detector simulation in Run 3

Uncertainties

Run 2 and Run 3 give similar uncertainties

JES:

8 % for lowest p_T,
~ 1 % at 100 GeV

JER:

~ 20 %

Largest uncertainties

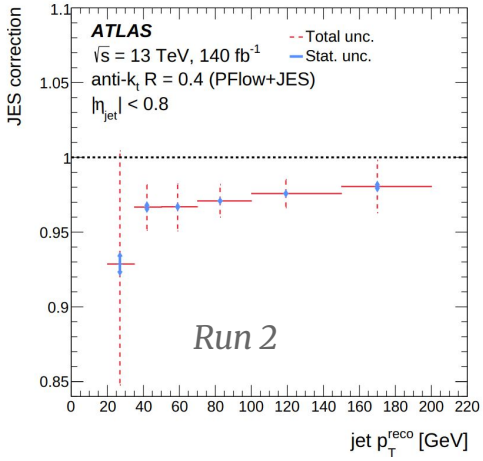
JES:

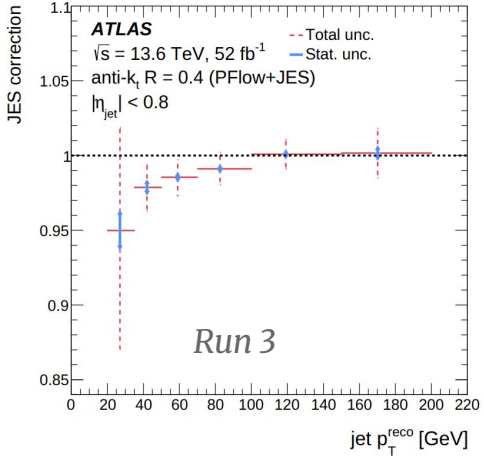
- JER
- α_s in FSR
- Pythia vs. Herwig for $t\bar{t}$

JER:

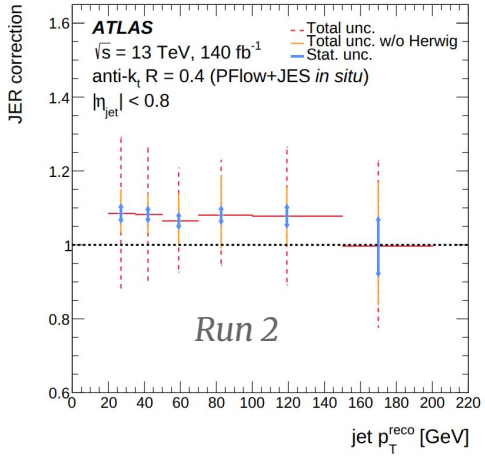
- **Pythia vs. Herwig for $t\bar{t}$**
- α_s in FSR
- JES

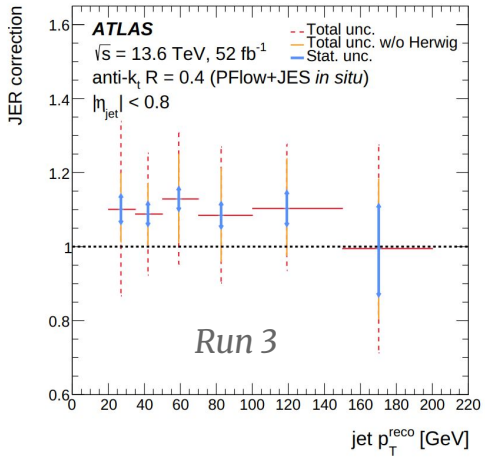
JES





JER





Summary

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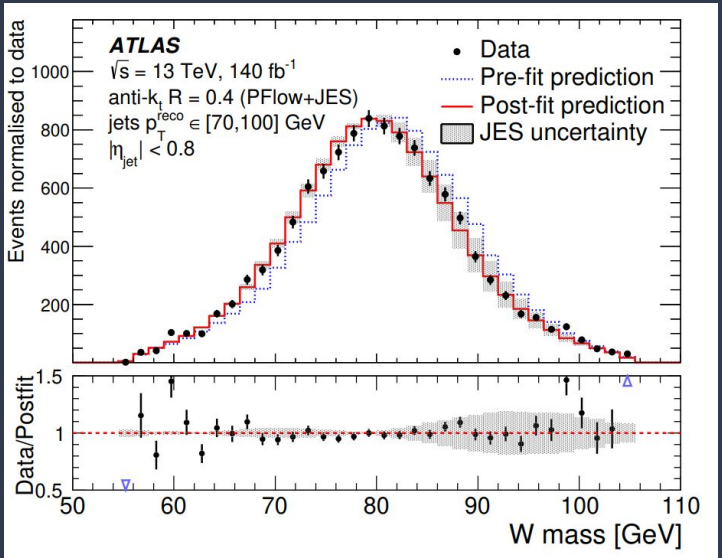
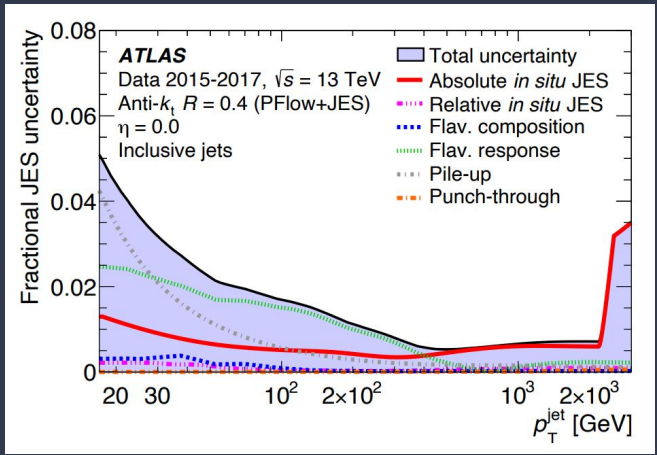
- JES and JER *in-situ* calibration using hadronic W mass
  - measuring JES and JER separately
- only done before in ATLAS as a cross check in 7 TeV, never actually used for calibration
- results for full Run 2 and partial Run 3 (2022 + 2023)
- accepted by EPJC





- dominant uncertainties: top quark modelling (α_s FSR and Pythia vs Herwig)
- potential to reach 0.5% in JES and 10% in JER if top quark modelling can be improved

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Backup

JES & JER from W

Applying Forward-Folding

not applied if the following criteria are not met
(treated as "background" for JES/JER in such case)

$$p_{\mathrm{T}}^{\mathrm{folded}} = s \cdot p_{\mathrm{T}}^{\mathrm{reco}} + (p_{\mathrm{T}}^{\mathrm{reco}} - \mathcal{R} \cdot p_{\mathrm{T}}^{\mathrm{gen}}) \cdot (r - s)$$

Selection

require **|η| < 0.8**
split in analysis regions
all cuts applied **after** the folding
- also $\chi^2 < 1$ and $E_T^{miss} > 30$ GeV

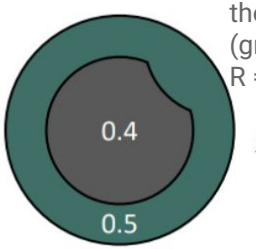
Truth jet matched to each reco jet

- look for truth jet within ΔR = 0.2 from reco jet
- p_T > 10 GeV for truth jets
- no multi-match

Isolation of the jets

- **f_{iso}< 0.3** requirement for reco jets
- require **ΔR > 0.5** between matched truth jet and its closest truth jet
- **no truth electron or muon** within ΔR < 0.5 of the reco jet

$$f_{\mathrm{iso}} = \frac{p_{\mathrm{T}}^{\mathrm{iso}} - \rho A_{\mathrm{iso}}}{p_{\mathrm{T}}^{\mathrm{Jet}} - \rho A_{\mathrm{Jet}}},$$



the isolation annulus (green) around jet with R = 0.4 (grey)

$$R_{\mathrm{iso}} = 1.25R$$

$p_{\mathrm{T}}^{\mathrm{iso}}$ p_T of all constituents within the isolation annulus

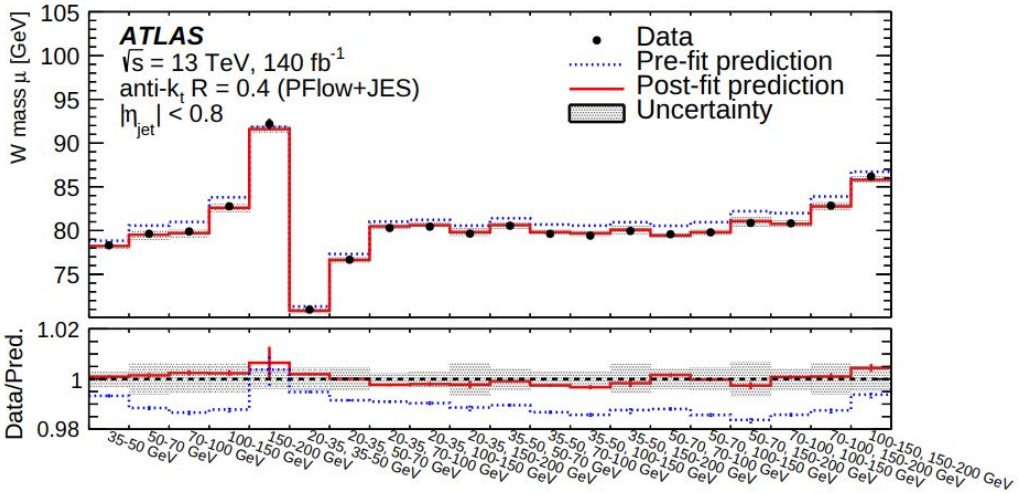
ρ pile-up density

A_{iso} area of the isolation annulus

$p_{\mathrm{T}}^{\mathrm{Jet}}$ p_T of all jet constituents

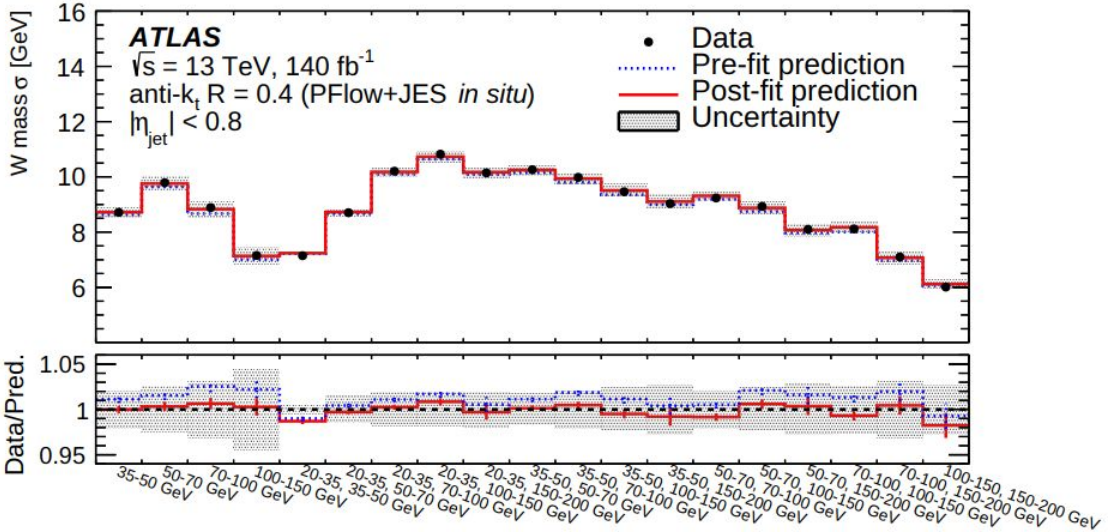
A_{Jet} jet active area

$$A_{\mathrm{iso}} = \pi R_{\mathrm{iso}}^2 - A_{\mathrm{Jet}}$$



JES fit ←

JER fit →



Category	JES uncertainty [%], Run 2					
Region [GeV]	$20 < p_{\mathrm{T}}^{\mathrm{reco}} < 35$	$35 < p_{\mathrm{T}}^{\mathrm{reco}} < 50$	$50 < p_{\mathrm{T}}^{\mathrm{reco}} < 70$	$70 < p_{\mathrm{T}}^{\mathrm{reco}} < 100$	$100 < p_{\mathrm{T}}^{\mathrm{reco}} < 150$	$150 < p_{\mathrm{T}}^{\mathrm{reco}} < 200$
JER	6.5	0.86	1.0	0.57	0.23	0.37
b-tagging	0.09	0.04	0.03	0.02	< 0.01	< 0.01
Electron	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.07	0.01	< 0.01	< 0.01	< 0.01	0.01
Muon	0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
$t\bar{t}$ Pythia versus Herwig	2.8	0.63	1.0	0.71	0.83	1.6
$t\bar{t}$ $\alpha_{\mathrm{s}}^{\mathrm{FSR}}$	2.9	0.88	0.60	0.50	0.19	0.24
$t\bar{t}$ CR variation	0.98	0.21	0.05	0.17	0.15	0.10
$t\bar{t}$ UE variation	0.04	0.34	0.05	0.07	0.06	0.18
$t\bar{t}$ other	0.80	0.40	0.17	0.20	0.18	0.40
Single-top tW modelling	0.26	0.02	0.02	0.03	0.07	0.07
Non-closure	0.37	0.12	0.04	0.06	0.04	0.06
Normalisation	0.09	< 0.01	0.02	< 0.01	< 0.01	< 0.01
Other	0.13	0.03	0.04	0.06	0.07	0.09
Statistical	0.64	0.23	0.13	0.11	0.12	0.23
Total systematic	7.8	1.5	1.6	1.1	0.92	1.7
Total uncertainty	7.8	1.5	1.6	1.1	0.93	1.7

Category	JER uncertainty [%], Run 2					
Region [GeV]	$20 < p_{\mathrm{T}}^{\mathrm{reco}} < 35$	$35 < p_{\mathrm{T}}^{\mathrm{reco}} < 50$	$50 < p_{\mathrm{T}}^{\mathrm{reco}} < 70$	$70 < p_{\mathrm{T}}^{\mathrm{reco}} < 100$	$100 < p_{\mathrm{T}}^{\mathrm{reco}} < 150$	$150 < p_{\mathrm{T}}^{\mathrm{reco}} < 200$
JES	3.1	1.6	5.8	8.2	6.1	6.1
b-tagging	0.6	0.6	0.5	0.3	0.3	0.4
Electron	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.1	< 0.1	< 0.1	< 0.1	0.1	0.3
Muon	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.2
$t\bar{t}$ Pythia versus Herwig	20	17	12	10	17	15
$t\bar{t}$ $\alpha_{\mathrm{s}}^{\mathrm{FSR}}$	3.3	3.1	1.6	1.6	1.3	< 0.1
$t\bar{t}$ CR variation	1.2	1.0	1.0	1.0	0.6	11
$t\bar{t}$ UE variation	0.8	< 0.1	0.7	1.4	1.1	5.9
$t\bar{t}$ other	1.8	2.4	2.2	4.3	3.1	4.7
Single-top tW modelling	0.2	0.2	< 0.1	0.3	0.2	< 0.1
Non-closure	0.6	0.6	0.7	0.4	0.6	1.6
Normalisation	0.9	0.7	0.5	0.3	0.3	0.4
Other	0.8	0.7	0.7	0.4	0.4	0.2
Statistical	2.1	1.8	1.8	2.0	2.8	7.6
Total systematic	20	18	14	14	18	21
Total uncertainty	20	18	14	14	19	22

Category	JES uncertainty [%], Run 3					
Region [GeV]	$20 < p_{\mathrm{T}}^{\mathrm{reco}} < 35$	$35 < p_{\mathrm{T}}^{\mathrm{reco}} < 50$	$50 < p_{\mathrm{T}}^{\mathrm{reco}} < 70$	$70 < p_{\mathrm{T}}^{\mathrm{reco}} < 100$	$100 < p_{\mathrm{T}}^{\mathrm{reco}} < 150$	$150 < p_{\mathrm{T}}^{\mathrm{reco}} < 200$
JER	6.0	0.72	0.78	0.61	0.23	0.33
b-tagging	0.10	0.05	0.04	0.03	0.02	0.01
Electron	0.03	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.04	0.01	0.01	< 0.01	< 0.01	0.01
Muon	0.03	< 0.01	< 0.01	< 0.01	< 0.01	0.01
$t\bar{t}$ Pythia versus Herwig	2.0	0.20	0.64	0.71	0.83	1.4
$t\bar{t}$ $\alpha_{\mathrm{s}}^{\mathrm{FSR}}$	3.0	0.96	0.56	0.36	0.23	< 0.01
$t\bar{t}$ CR variation	0.40	0.38	0.09	0.04	0.09	0.12
$t\bar{t}$ UE variation	0.08	0.46	0.27	0.24	0.16	0.41
$t\bar{t}$ other	1.7	0.59	0.09	0.17	0.33	0.48
Single-top tW modelling	0.22	< 0.01	0.01	0.03	< 0.01	0.01
Non-closure	0.43	0.18	0.07	0.03	0.06	0.10
Normalisation	0.14	0.03	0.02	< 0.01	< 0.01	< 0.01
Other	0.21	0.02	0.05	0.04	0.05	0.07
Statistical	1.2	0.37	0.20	0.17	0.18	0.36
Total systematic	7.3	1.5	1.2	1.1	0.97	1.6
Total uncertainty	7.4	1.5	1.2	1.1	0.98	1.6

Category	JER uncertainty [%], Run 3					
Region [GeV]	$20 < p_{\mathrm{T}}^{\mathrm{reco}} < 35$	$35 < p_{\mathrm{T}}^{\mathrm{reco}} < 50$	$50 < p_{\mathrm{T}}^{\mathrm{reco}} < 70$	$70 < p_{\mathrm{T}}^{\mathrm{reco}} < 100$	$100 < p_{\mathrm{T}}^{\mathrm{reco}} < 150$	$150 < p_{\mathrm{T}}^{\mathrm{reco}} < 200$
JES	3.3	5.0	9.5	11	11	11
b-tagging	0.7	0.7	0.6	0.3	0.4	0.8
Electron	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.1	0.3	0.2	< 0.1	0.2	0.4
Muon	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.1
$t\bar{t}$ Pythia versus Herwig	22	14	13	13	11	21
$t\bar{t}$ $\alpha_{\mathrm{s}}^{\mathrm{FSR}}$	4.5	4.0	2.7	1.2	1.3	1.7
$t\bar{t}$ CR variation	2.6	2.5	3.8	2.3	3.6	7.0
$t\bar{t}$ UE variation	4.1	1.0	0.1	1.1	2.7	0.4
$t\bar{t}$ other	3.8	2.6	4.1	5.2	3.8	4.9
Single-top tW modelling	0.2	0.2	0.3	0.1	0.3	0.9
Non-closure	1.1	0.7	0.8	0.3	1.0	2.2
Normalisation	0.7	0.6	0.6	0.2	0.3	0.4
Other	0.9	0.7	0.8	0.5	0.5	1.4
Statistical	3.7	3.0	3.0	3.3	4.5	12
Total systematic	23	16	17	18	16	25
Total uncertainty	24	16	18	18	17	28