Jet physics at the LHC: status from reconstruction to analysis

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A personal and biased selection of results. An experimentalist view.

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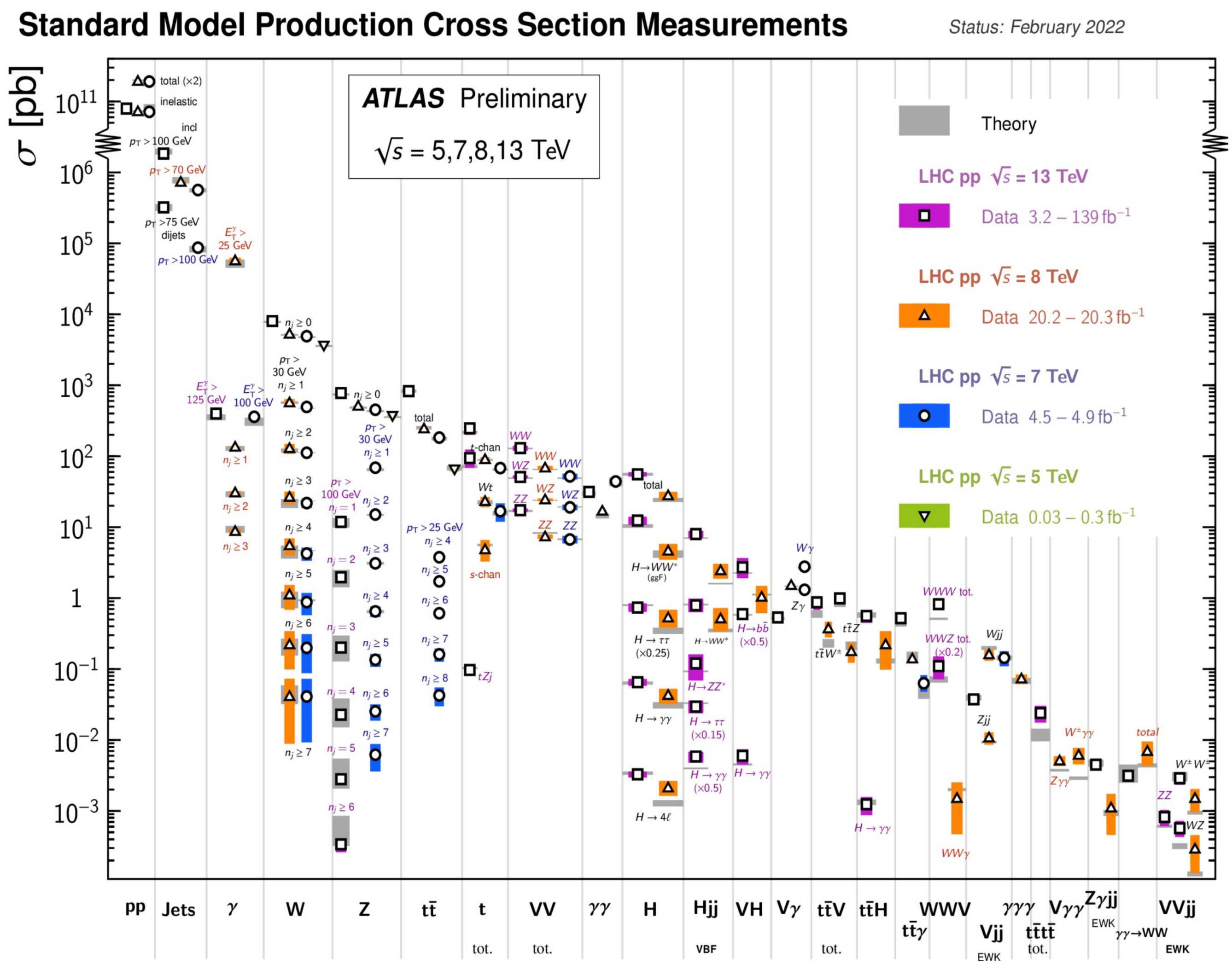
ATLAS EXPERIMENT LPNHE PARIS

The LHC is a very jetty place

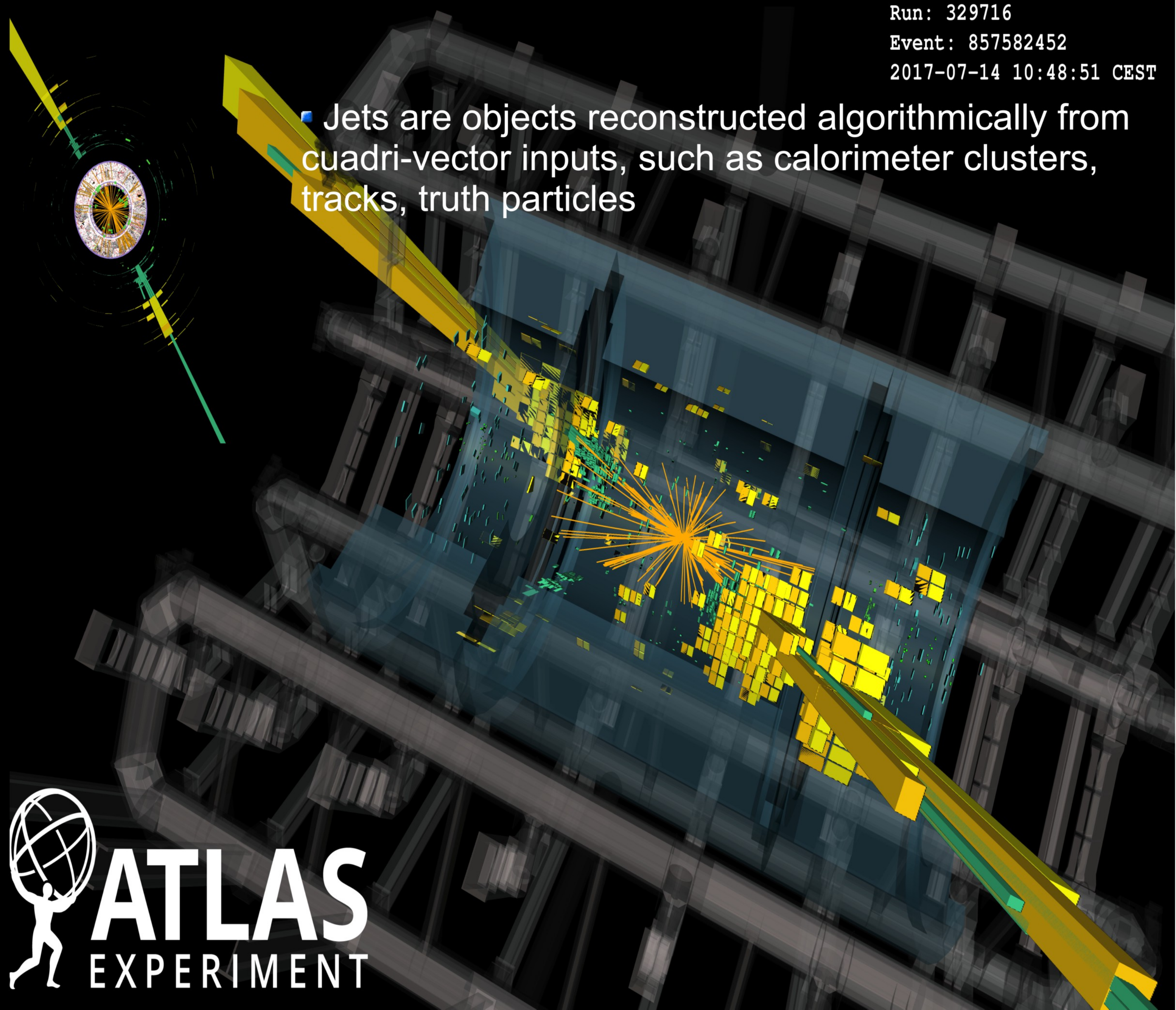
- Strongly interacting quarks and gluons produced in the LHC collisions hadronise and produce a cascade of particles, which can be collected using some specialised algorithms to build what we call "jets"
- More than 90% of physics analyses done in ATLAS use jets in one way or another



The LHC is a very jetty place

Constituents/
inputs

- Jets are objects reconstructed algorithmically from cuadri-vector inputs, such as calorimeter clusters, tracks, truth particles

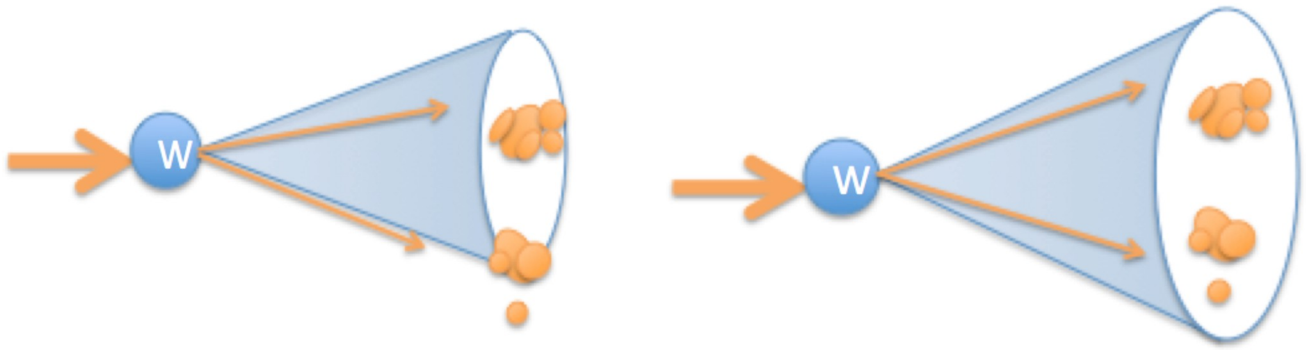


The LHC is a very jetty place

Constituents/
inputs

Jet algorithm/
radius

- A jet can be proxy for quark/gluons but also for other particles decaying to quarks/gluons, e.g. W/Z/Higgs bosons, top quarks.
  - Small-radius jets are proxies for quark/gluon jets
  - Large-R jets are often used to reconstruct boosted particles decaying hadronically



The LHC is a very jetty place

Constituents/
inputs

Jet algorithm/
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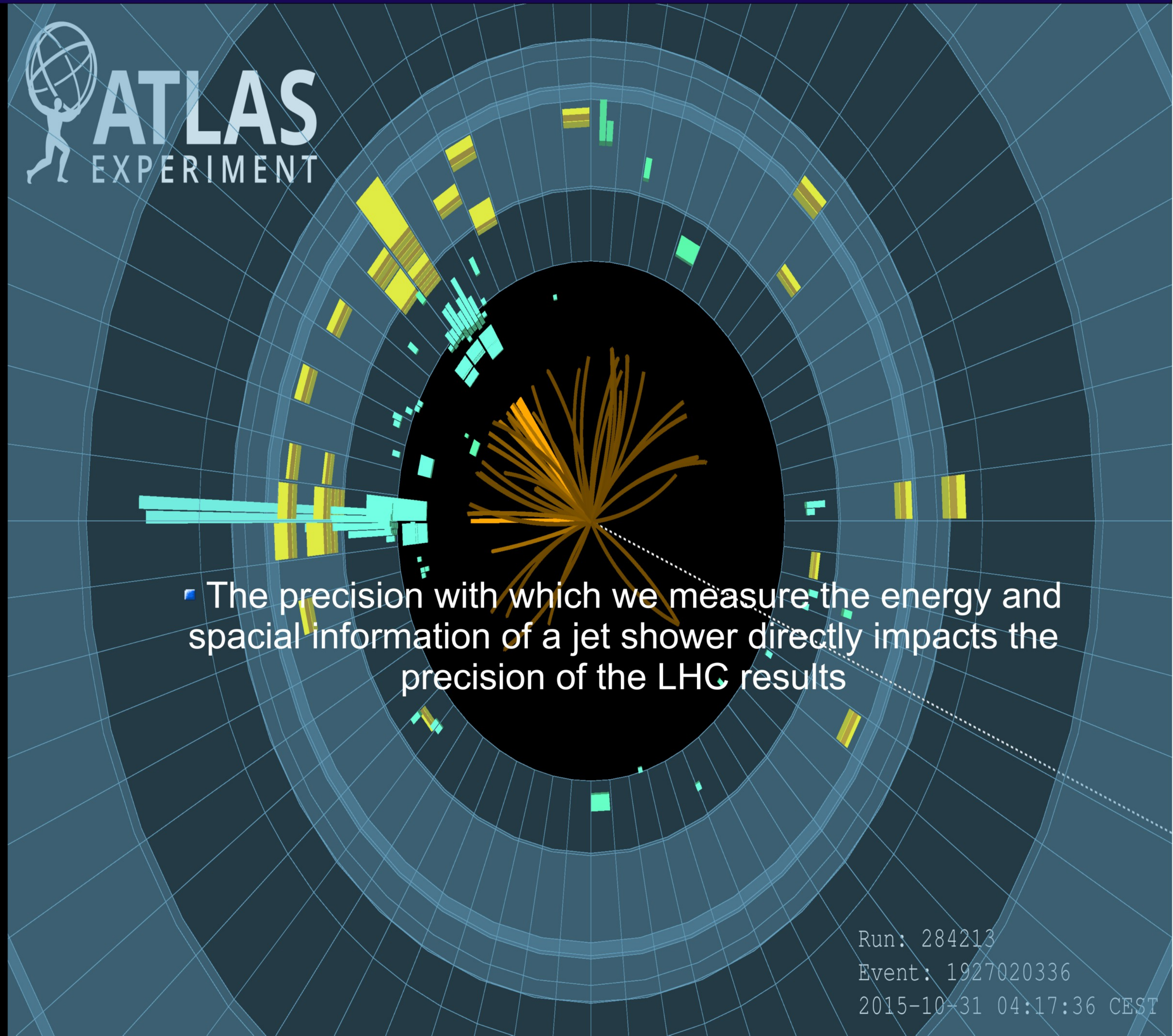
Calibration

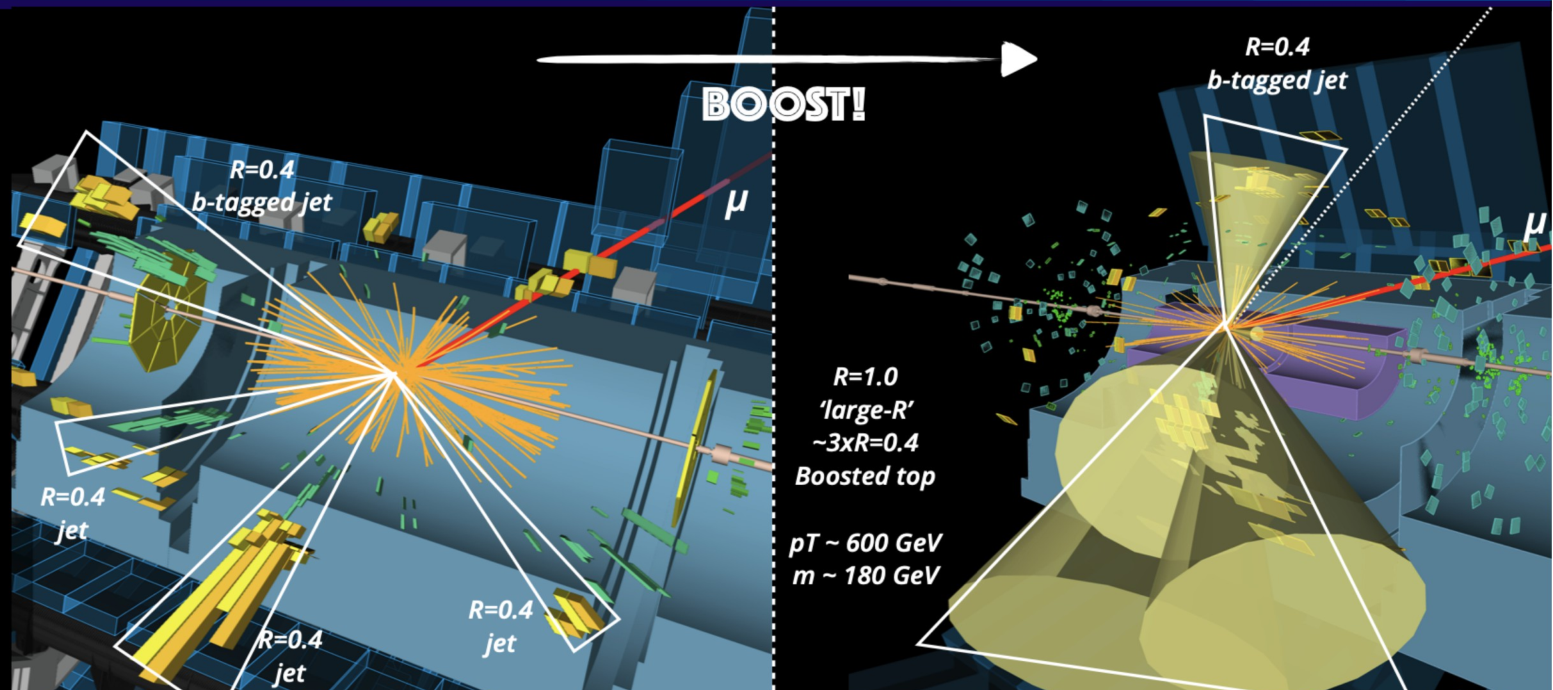


- The precision with which we measure the energy and spacial information of a jet shower directly impacts the precision of the LHC results

The LHC is a very jetty place

Constituents/ inputs

Jet algorithm/ radius

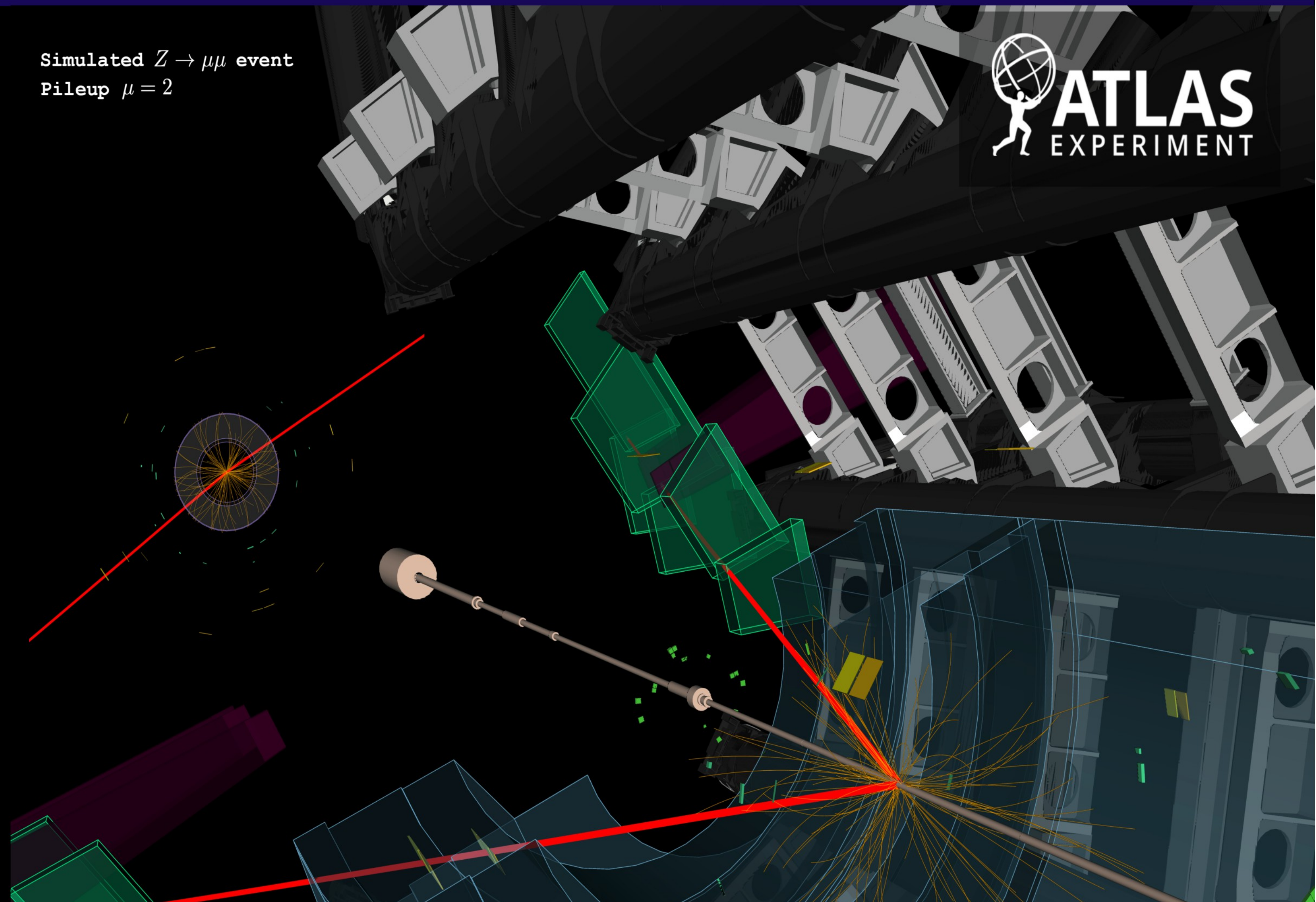


Calibration

Jet tagging

- And studying its substructure we can identify which particle is at the origin of the jet, e.g. is a quark or a gluon? Or rather a vector boson? Is it Higgs or a top quark?

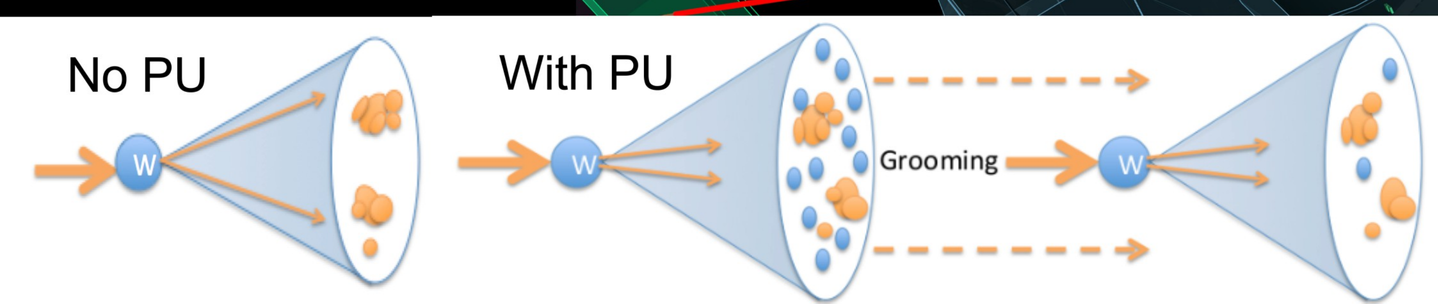
The LHC is a very jetty place



There are many challenges and the large number of additional interactions (pile-up) is one of them

PU treated for jets at different levels:

- in the calibration
- at the inputs
- using grooming techniques for large-radius jets



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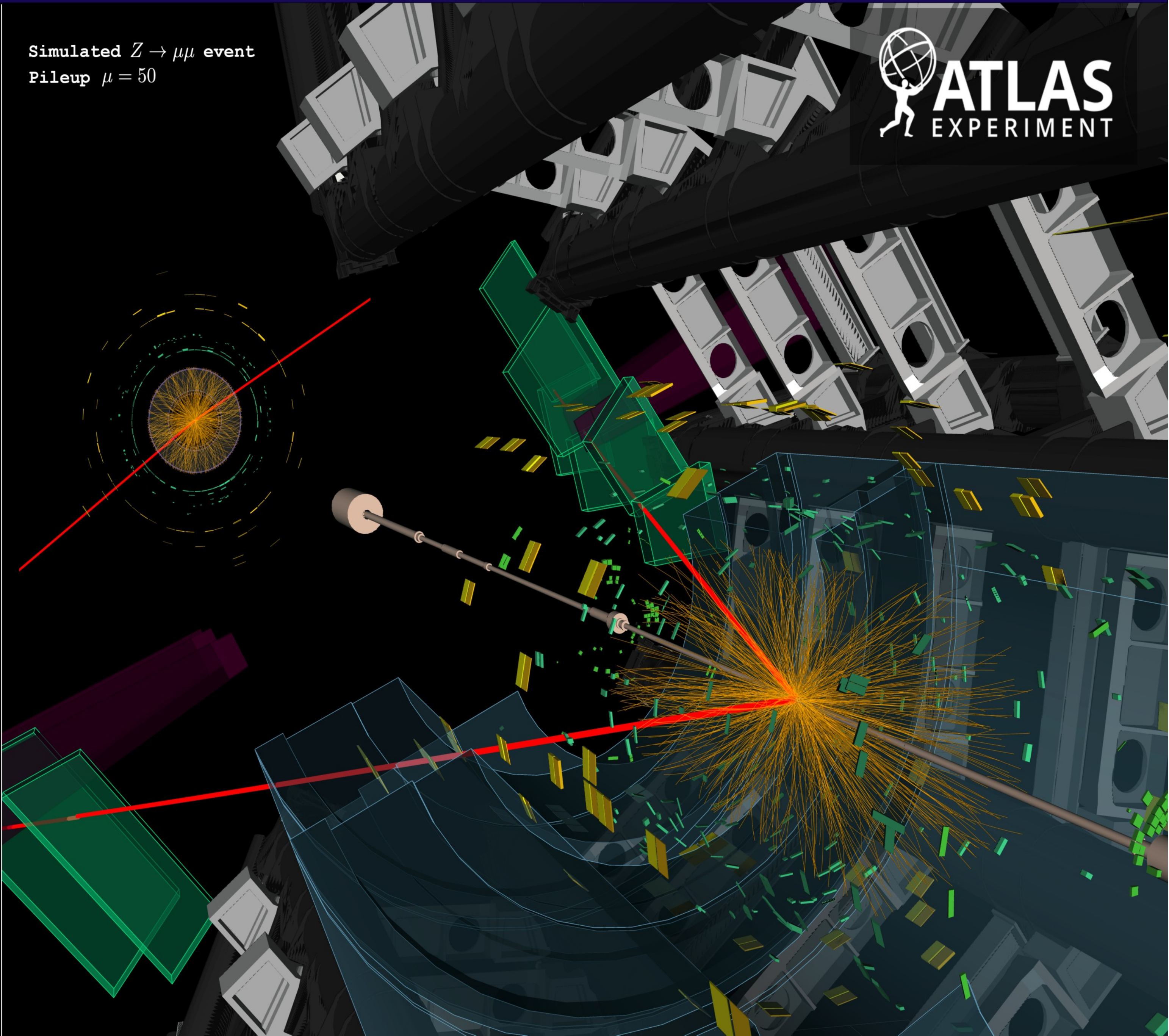

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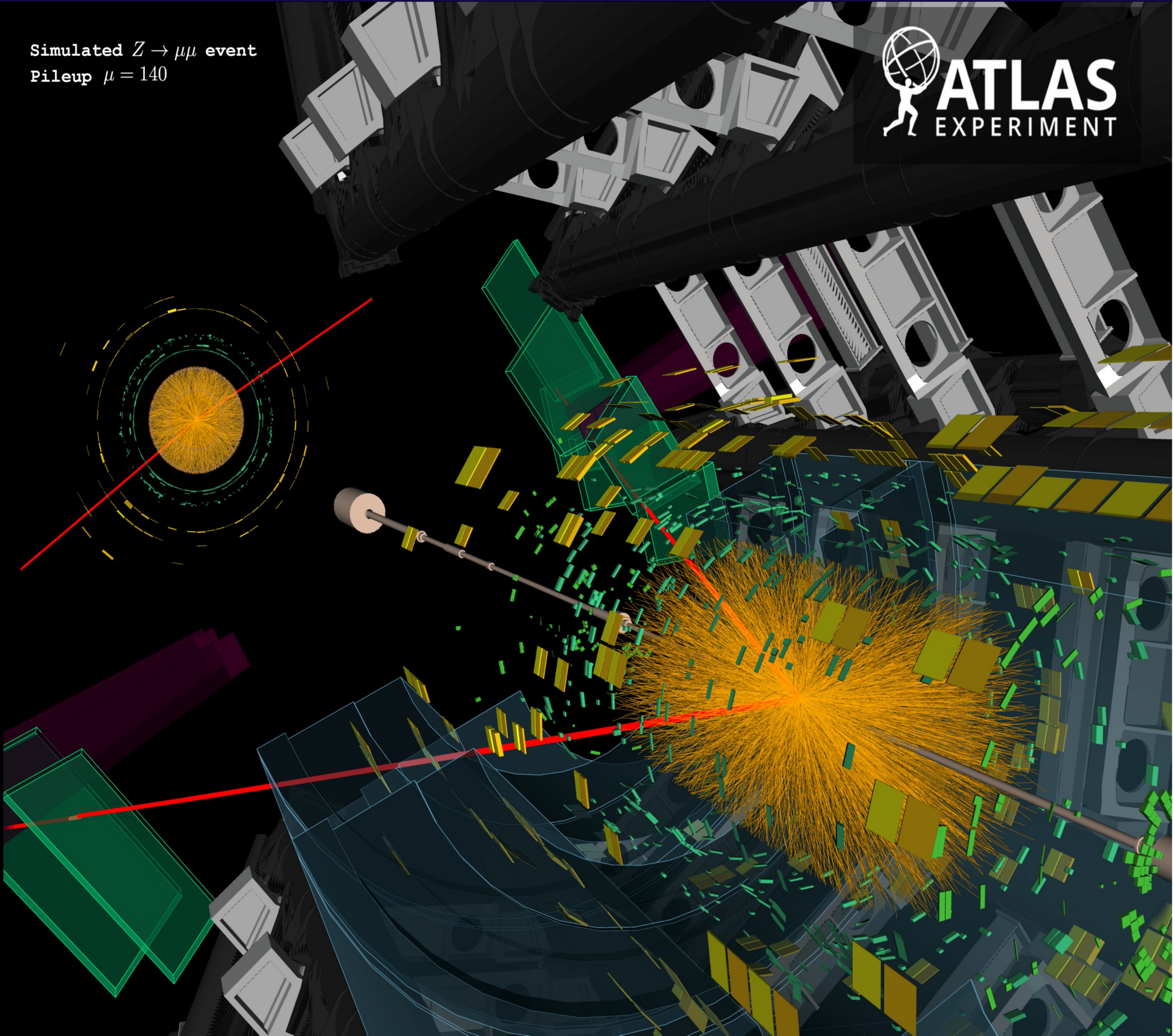
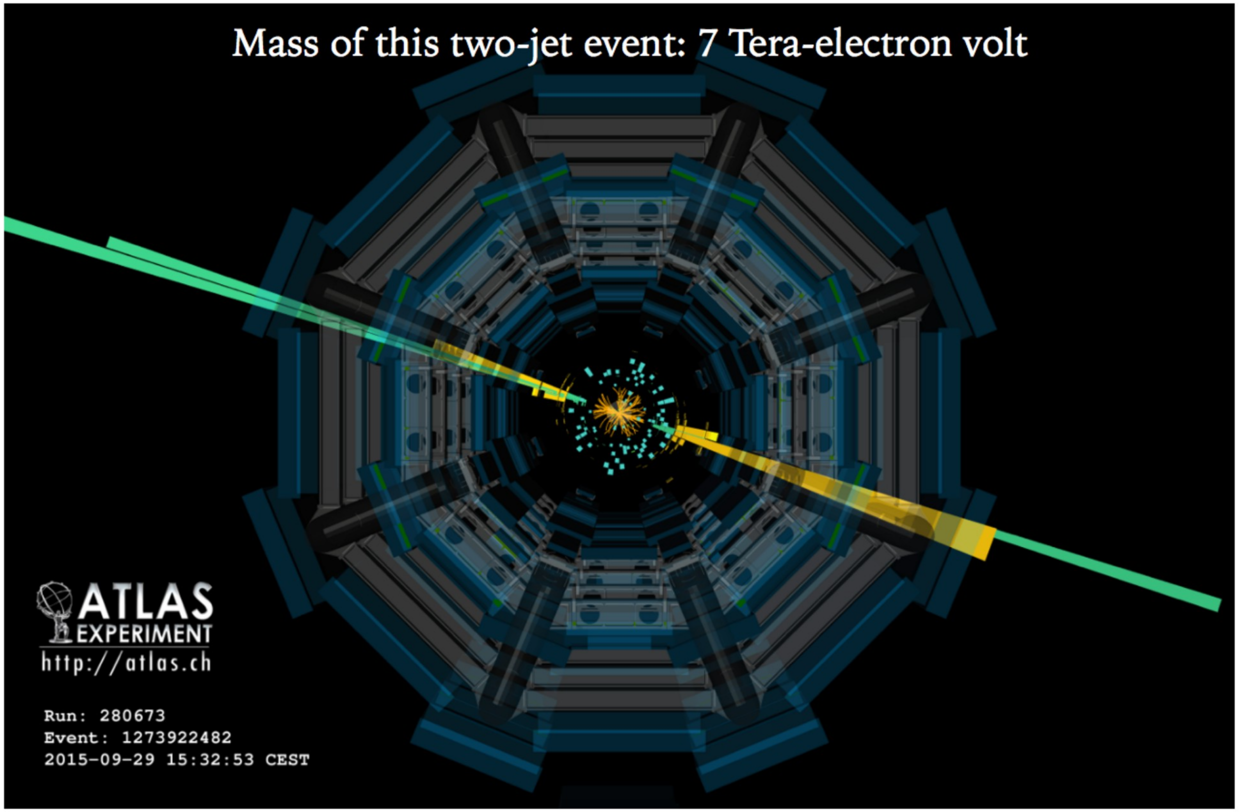


The LHC is a very jetty place

- ATLAS has achieved percent-level precision during Run-2

- Before being able to use these interesting and abundant objects in your analysis there are many steps to take and experimental challenges to hadronic object reconstruction

- Today:
  - Our detector
  - Jet performance overview (with focus on new ideas/developments for Run-3)
  - Closing with a few analysis examples using jets

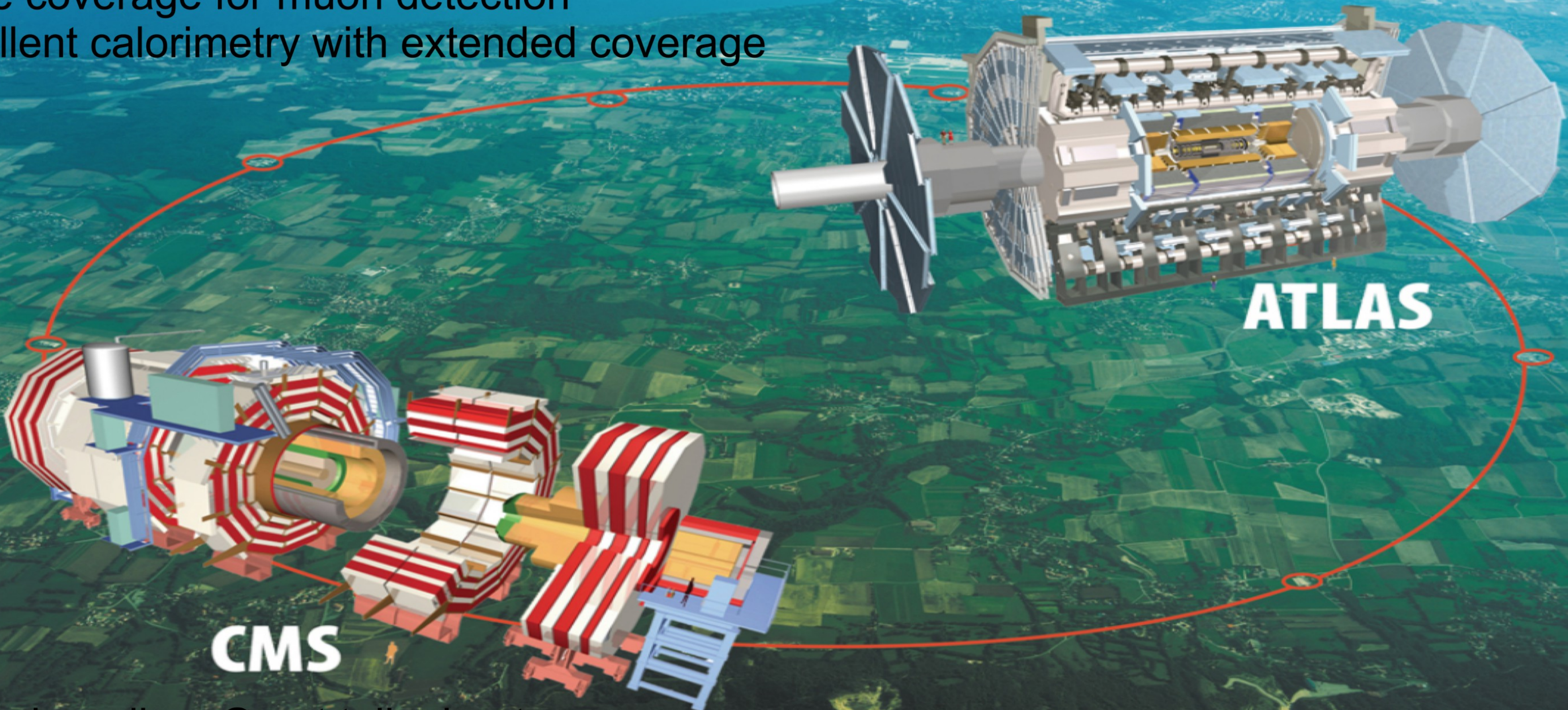


Our tools
The LHC and ATLAS

- A proton-proton collider of 27 Km circumference situated at CERN. Currently running at an center-of-mass energy of 13 TeV since 2015

- Fantastic machines with capabilities beyond design

- ATLAS is a non-specialized detector: broad range of physics, same concept, different technologies
  - Excellent vertex and tracking systems
  - Large coverage for muon detection
  - Excellent calorimetry with extended coverage



Additional reading: Great talk about
Calorimetry in HEP by P. Loch

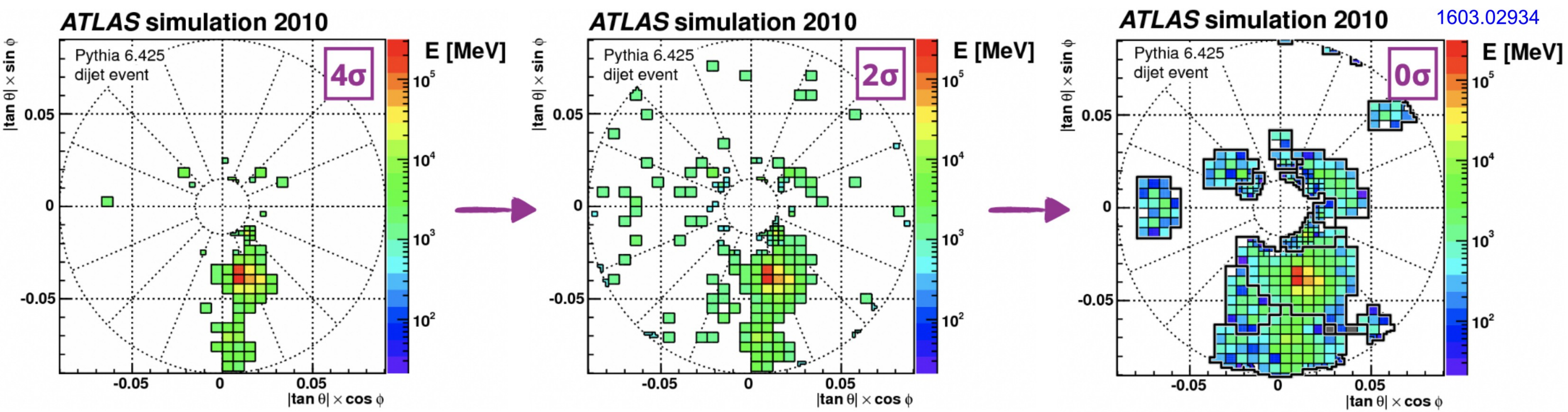
Jet constituents/inputs

- **During Run-1 mostly calorimeter information** was used to build our jets
  - 3D clustering algorithm: topological clusters (connected groups of cells which are seeded by a cell with |E| > 4σ)

- **In Run-2 we started exploiting as well the information from the inner detecto**r: good angular resolution of tracker and good energy resolution from calorimeter
  - Particle Flow (**PFlow**) algorithm
  - Track-calo cluster (**TCC** algorithm)

- Current state of the art is combination of TCC and Pflow
  - Unified Flow Objects (**UFO**)

- Let's briefly review each one of them



PFlow algorithm

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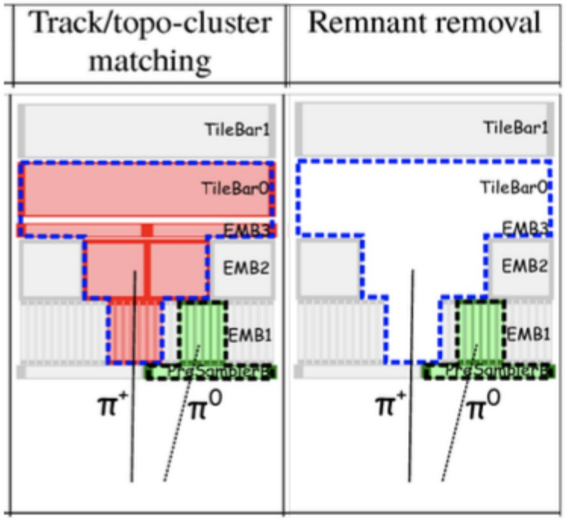
- Aims to improve jet reconstruction by using tracks as they have **better resolution at low p_T, and can separate pile-up**

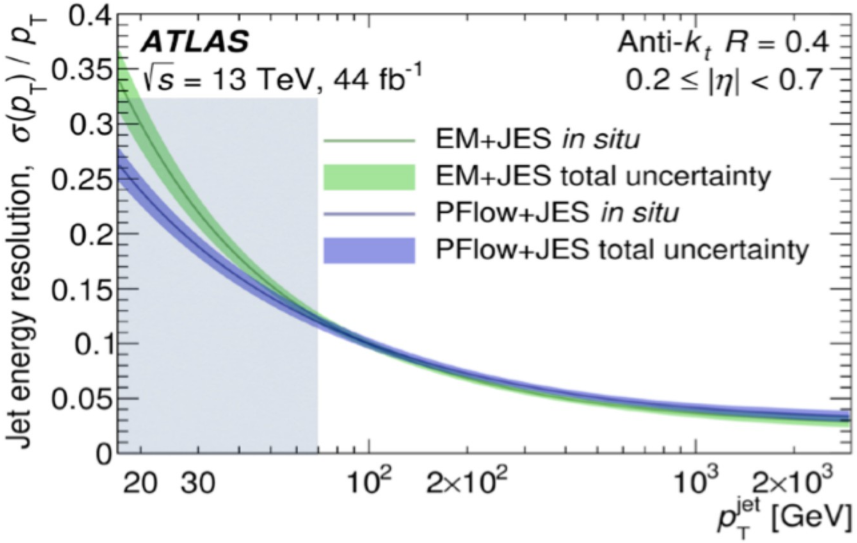
- It goes as:
  - Tracks with good momentum resolution extrapolated to calorimeter
  - Energy deposits associated with selected tracks are subtracted from the clusters
  - If the remaining energy in the system is consistent with the expected shower fluctuations of a single particle's signal, the topo-cluster remnants are removed



- Relies heavily on understanding of single-hadron response (E/p)

- In dense environments the cell-by-cell substraction becomes difficult and PFlow reverses itself to using EM-scale topoclusters in this cases
  - *Performance degraded at high p_T*

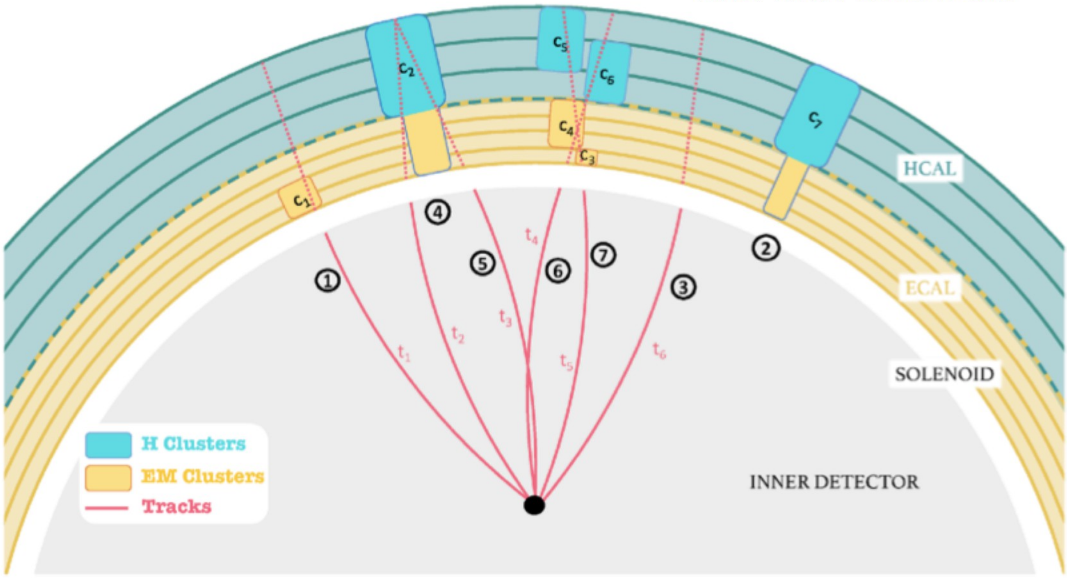
- **Baseline inputs/algorithm for R=0.4 jets**



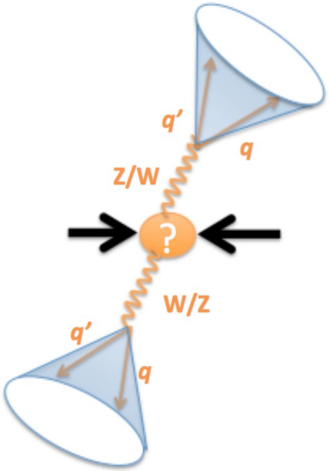
Track-calo cluster (TCC) algorithm

- **Also match tracks to topoclusters**
  - At high p_T topoclusters merge due to the finite cell granularity in the Tile calorimeter
  - TCC algorithm effectively uses tracks to split up these large clusters
  - **Improving the mass (and sub-structure) resolution at high p_T**

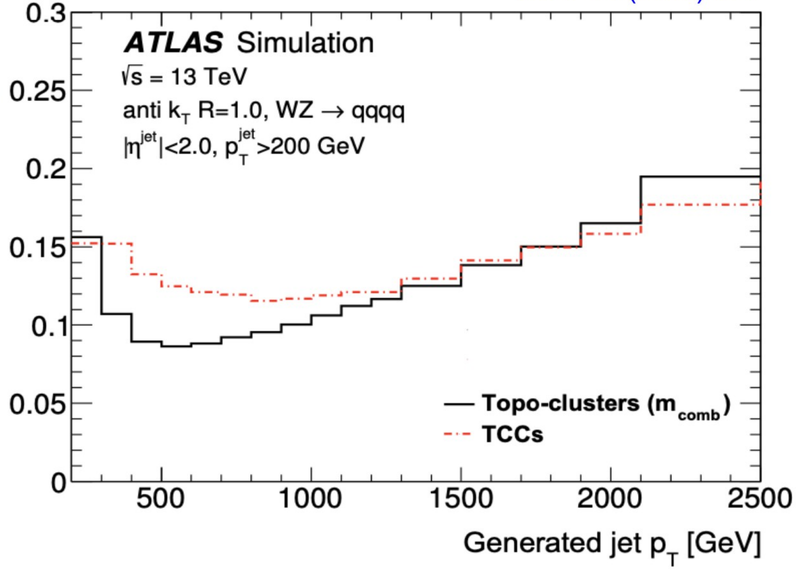
ATL-PHYS-PUB-2017-015



- **An example of use: diboson resonance searches**... Good improvement observed when using TCC!



JHEP 09 (2019) 091



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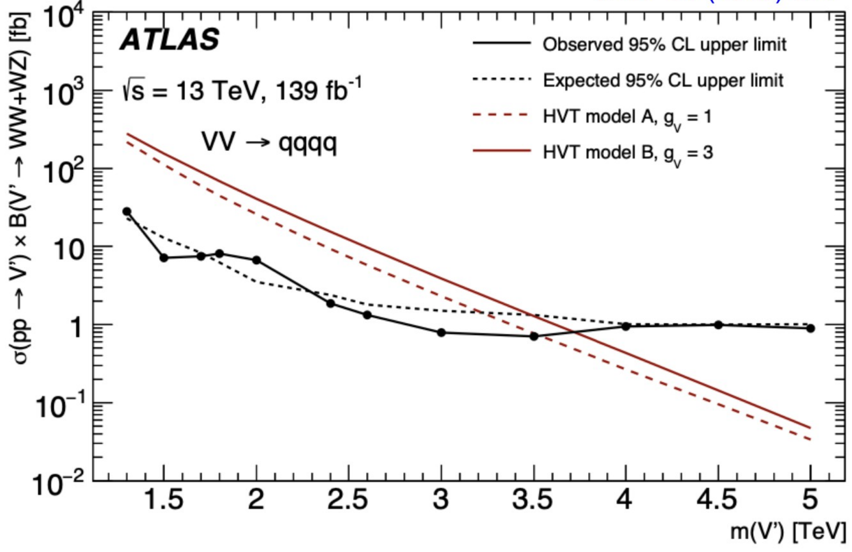


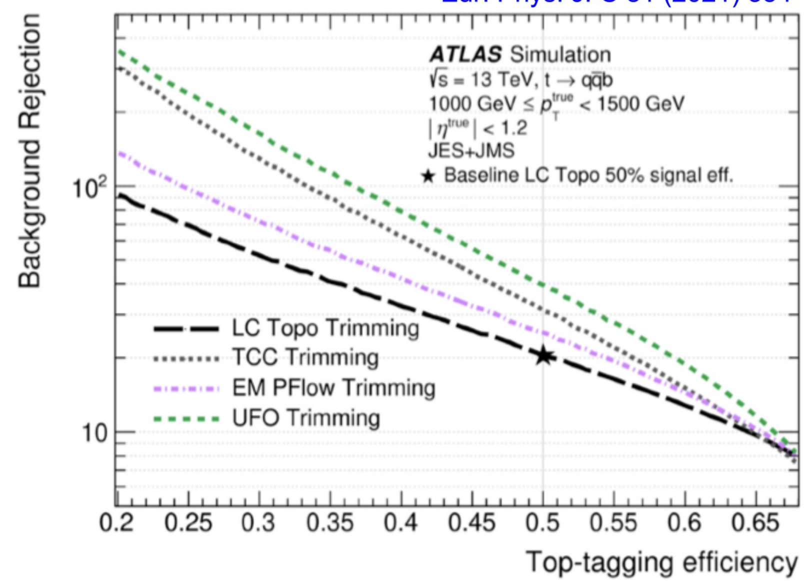
Unified Flow Objects (UFO)

- **UFO combines both TCC and PFlow**:
  - TCC cluster splitting in dense environment case where PFlow would disable itself

- The **best mass resolution across pT and show the best jet tagging capabilities** (~x2 background rejection)

- Currently **being commissioned as baseline for large-radius jets**, following a long-term reoptimisation campaign duringf Run 2 and LS2

Eur. Phys. J. C 81 (2021) 334



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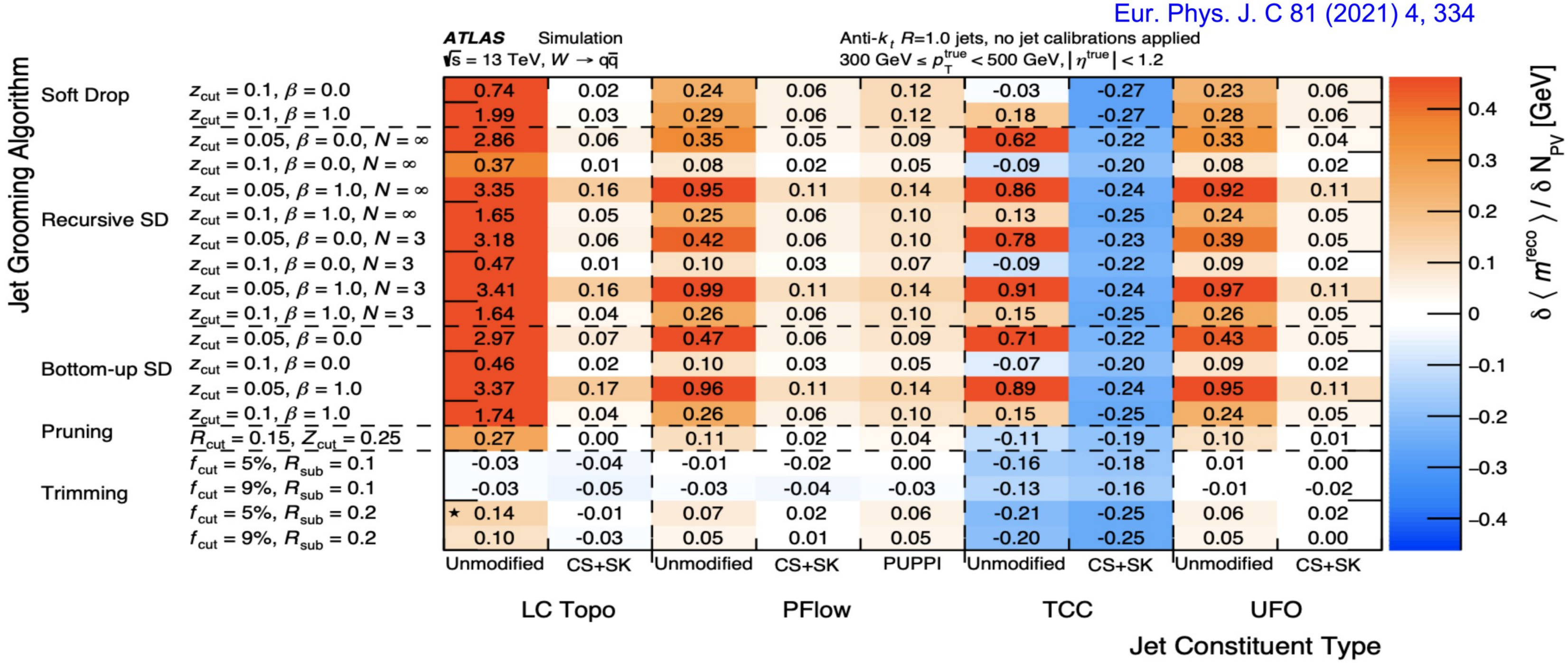
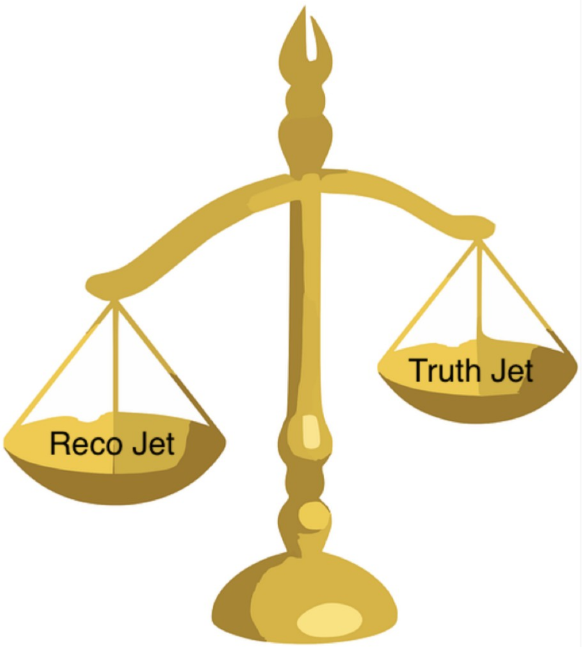


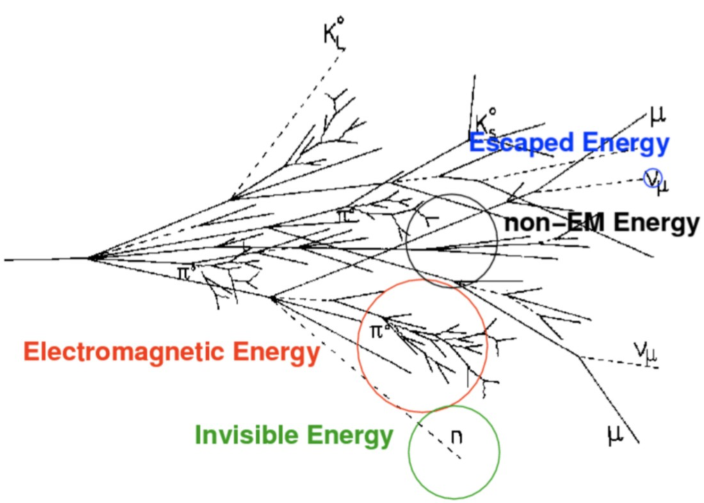
Jet calibration

- The sensitivity of searches and measurements that jets depends on an **accurate knowledge of the p_T and mass responses of the detector**
  - Small-R jets: energy scale (JES) then position calibrated
  - Large-R jets: calibrations for energy, position and mass (JMS) as well

- **Why we need it?**
  - Calorimeter non-compensation (e/h > 1)
  - Dead material: energy deposited in non-instrumented region
  - Out of cone jet: particle shower outside the jet cone
  - Energy deposits below noise thresholds
  - Pile-up
  - Leakage: energy deposited beyond the calorimeter region (punch-through)

- **How do we calibrate jets?**
  - A combination of MC and in-situ techniques that will be briefly summarised in this talk





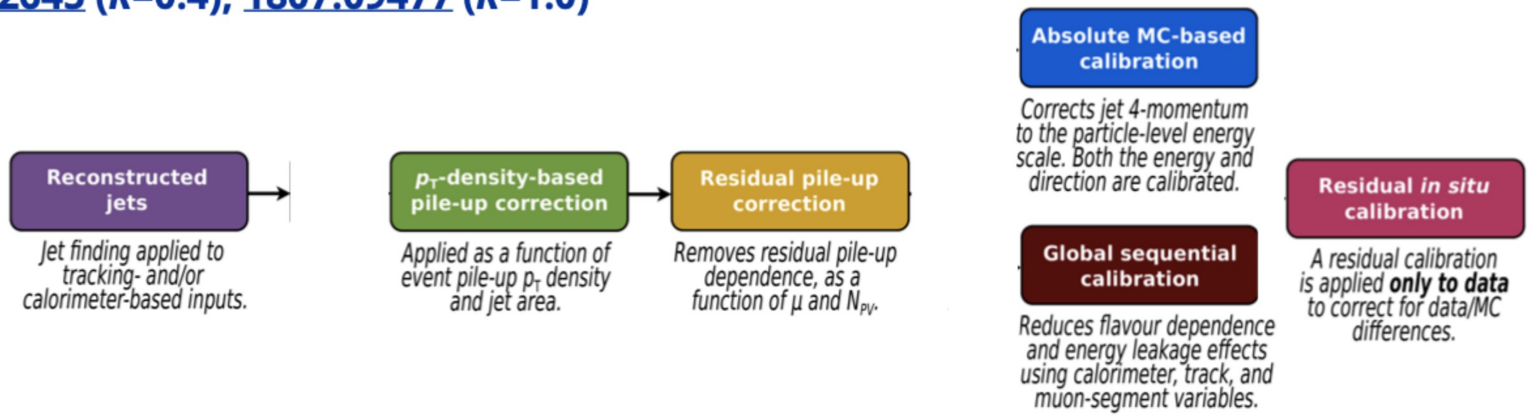
Hadronic showers are much more varied than EM showers

Jet calibration chain

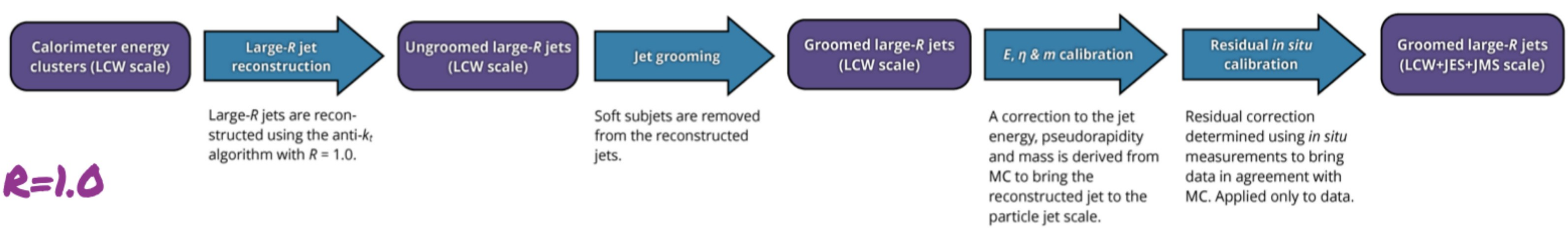
From Matt LeBlanc Semi-Visible Jets Workshop @ ETH Zurich, July 2022

ATLAS 2007.02645 (*R*=0.4), 1807.09477 (*R*=1.0)

R=0.4

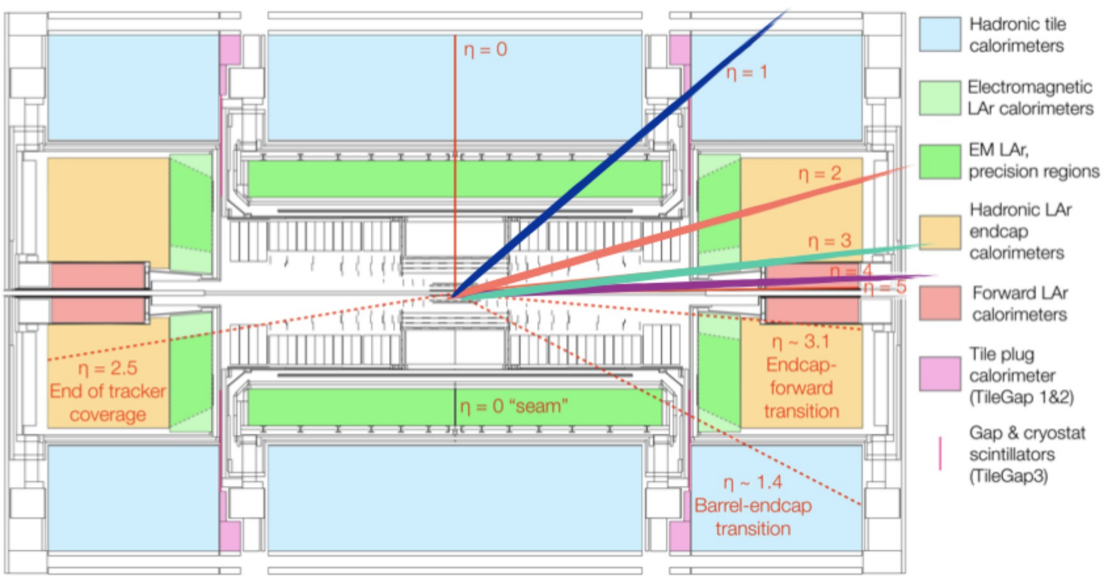


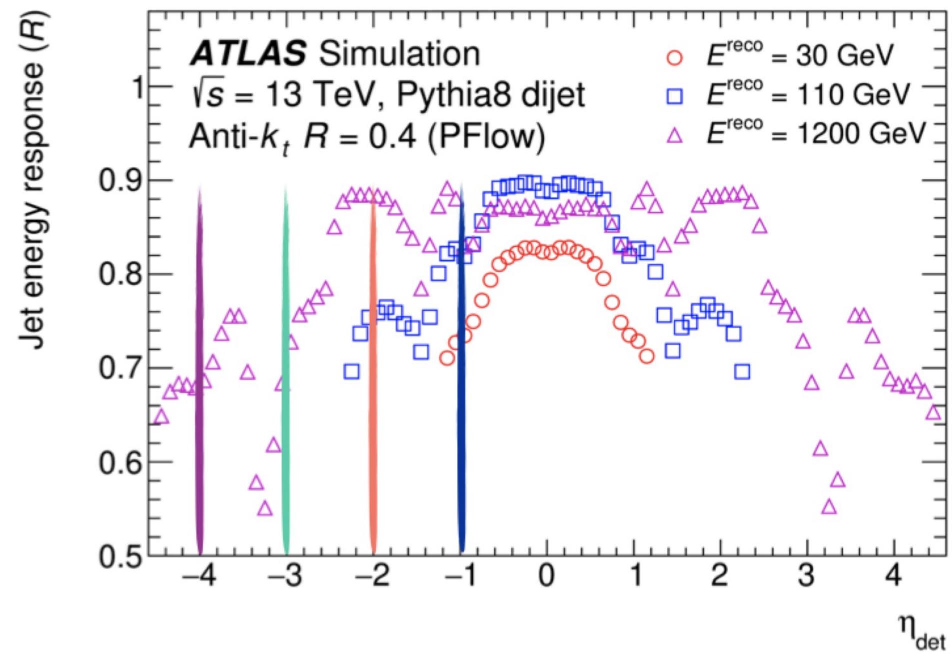
R=1.0



- The **jet calibration sequence** corrects for pile-up, restores $\langle p_T^{reco}/p_T^{true}\rangle = 1$ with MC-based correction, improves the resolution, and then corrects the response in data to match that in MC
- **Many steps which need to be performed sequentially!**

Jet calibration: Absolute MC calibration





- The **jet response gets closer to 1 after the absolute MC calibration**
- Particles only included in truth-jet reconstruction if they will deposit energy in the calorimetry systems (invisibles, muons excluded)

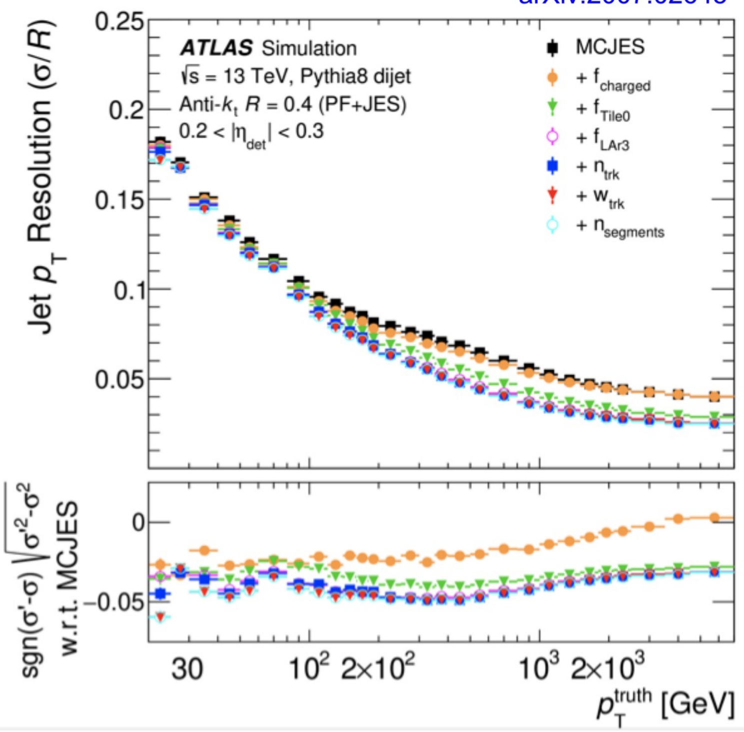
From Matt LeBlanc Semi-Visible Jets Workshop @ ETH Zurich, July 2022

Jet calibration: Global Sequential Calibration

- The **scale depends on some of the visible features of the jet** eg.
  - fraction of energy in a calo layer (fTile0 is sensitive to energy in dead material)
  - number of tracks (is sensitive to quark vs gluon nature)
  - charged fraction, etc., (in Pflow the charged fraction is calibrated
- **The resolution can be improved by removing these dependencies**
- Currently, this is done sequentially for 6 variables, resulting in a significantly better resolution

- A **new DNN-based version of this calibration is being commissioned now**. It uses additional jet and event information and takes into account correlation between these variables
  - Greater improvements in the jet resolution over the traditional GSC approach

arXiv:2007.02645



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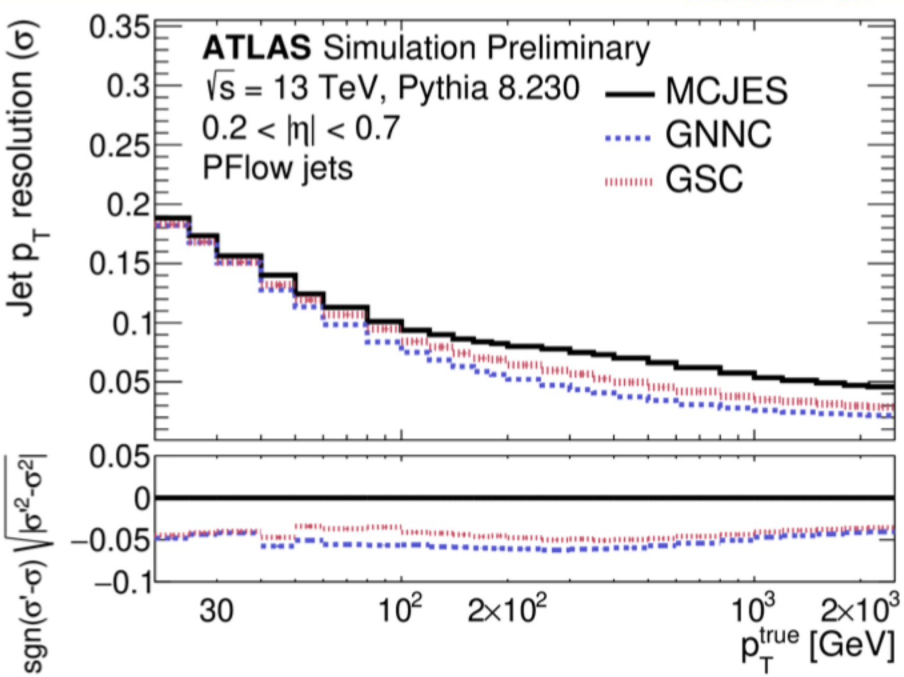
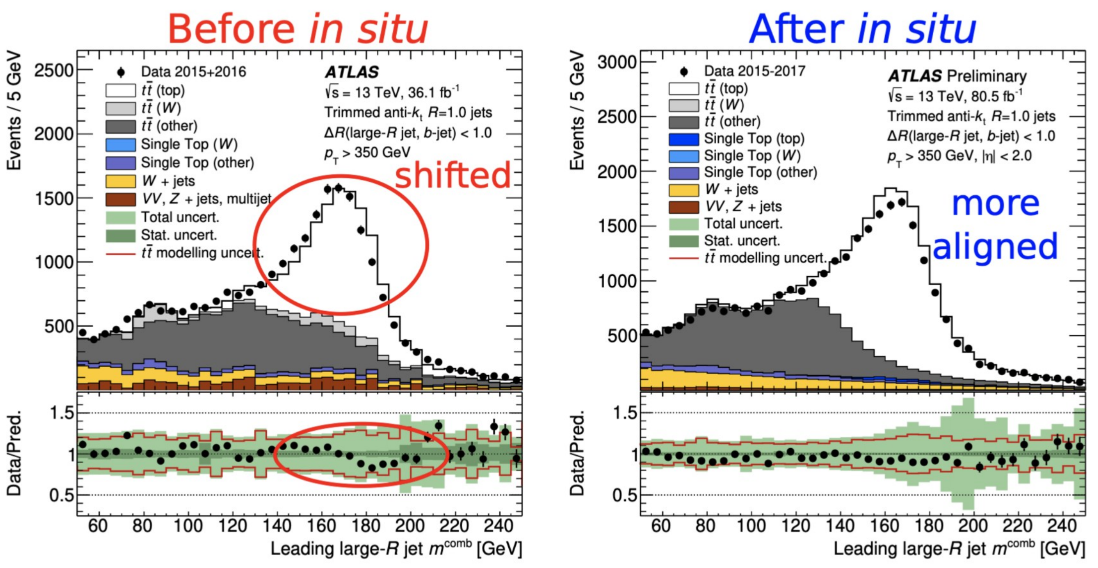


Taken from Chris Young

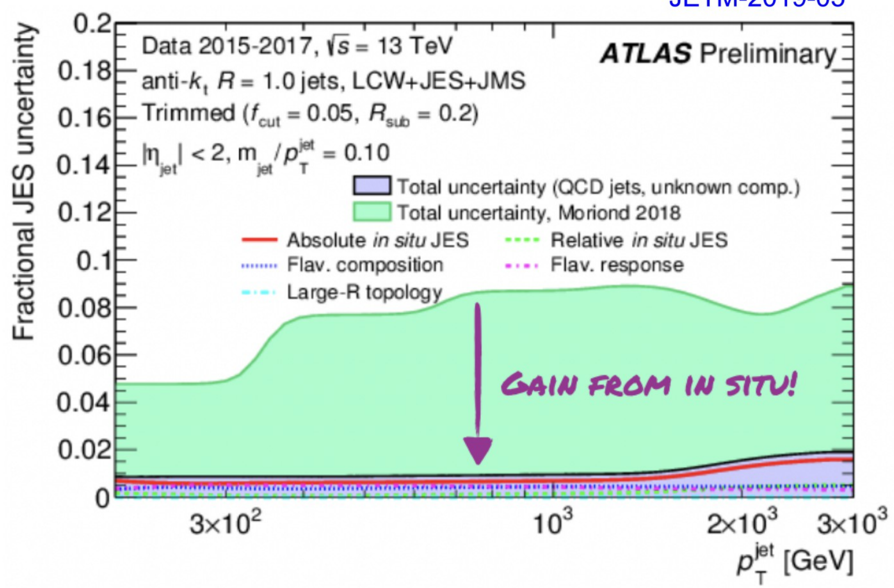
Jet calibration: in-situ steps

- The **MC-based parts of the calibration assumes MC perfectly represents data,** which is not always correct!
  - If all we can do is bracket possible differences, then we have defined large uncertainties
  - We would rather correct differences, such that $\langle X_{data}^{reco} \rangle = \langle X_{sim}^{reco} \rangle$, with residual uncertainties



- This is possible by comparing a probe jet quantity against a precisely known reference
  - We can measure a quantity of interest in both data and simulation, correcting for differences

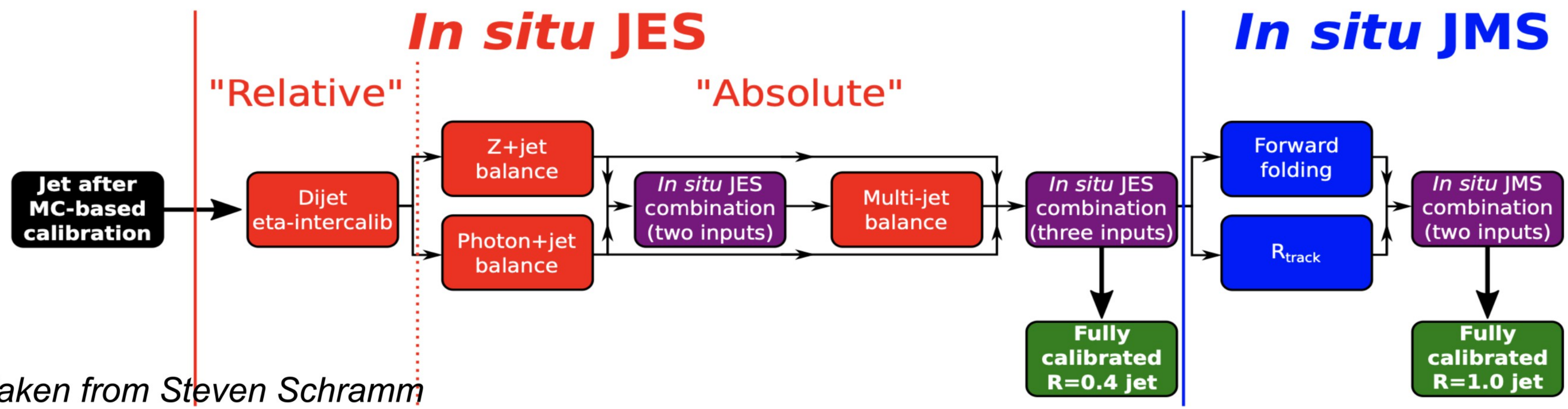
JETM-2019-05



- **A complete in situ JES calibration provides huge gains wherever it's possible!**

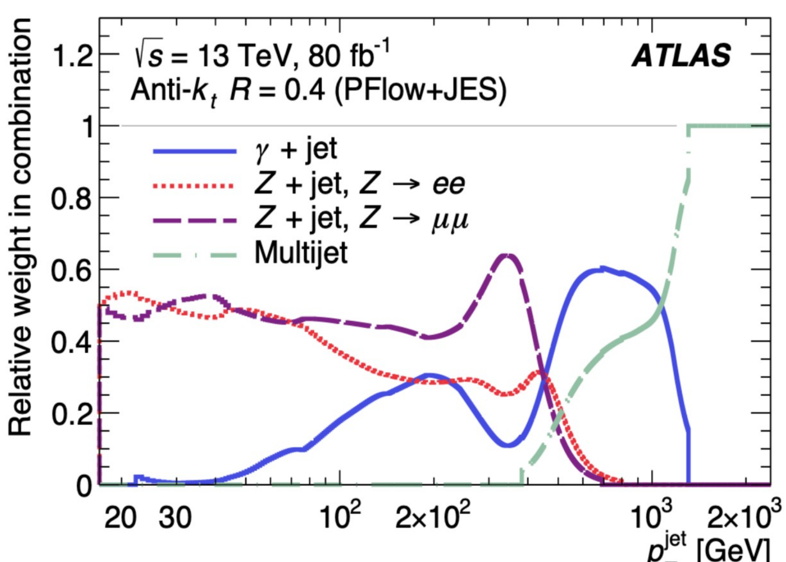
Jet calibration: in-situ steps

- **The final jet scale correction consists of**: using di-jets to correct scale vs η, then a combination of Z + jet, γ+jet and multi-jet balance to get the final correction
- There are **a few other steps for the in situ jet resolution**: Use dijet event imbalances, together with random cones to constrain the noise term



Taken from Steven Schramm

- We rely on balance techniques which are sensitive to MC modeling of out-of-jet radiation, additional jet production, etc.
- In the high p_T scale is also measured for single $\pi^{\pm}$ using $W \rightarrow \tau\nu$ to ~0.5%
- **Each one of this steps is an analysis in itself! They are complementary**



Jet calibration: flavour and modelling uncertainties

- **Recent developments will allow us to improve even more our jet calibration uncertainties**
- Previously the flavour treatment was based on the sample composition and the difference in response of gluon initiated jets between different generators
- Recent calibrations now available to remove this effect when comparing generators in analyses - see > 30% reduction in Pythia-Herwig uncertainties in first examples!

- **This will be very useful for many analyses for which the jet flavour uncertainties were dominant**

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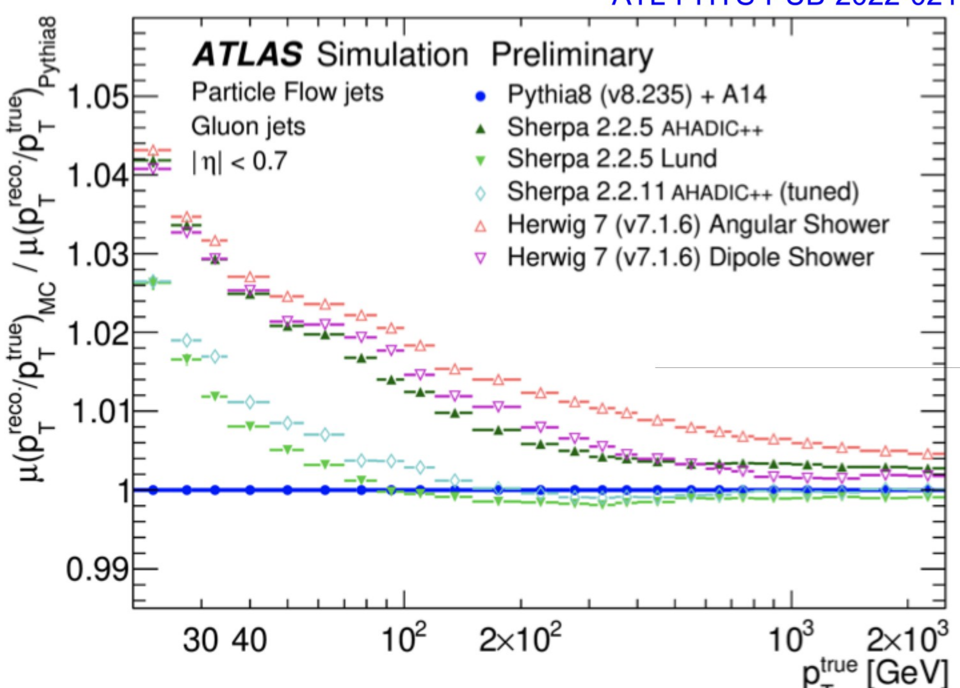
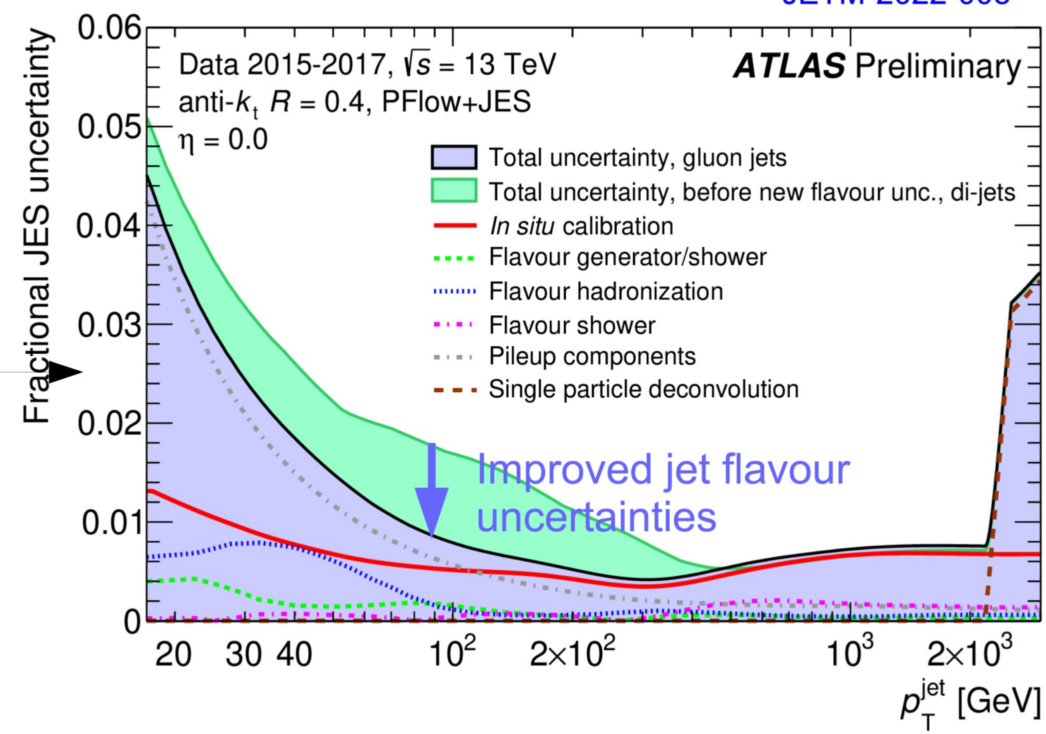


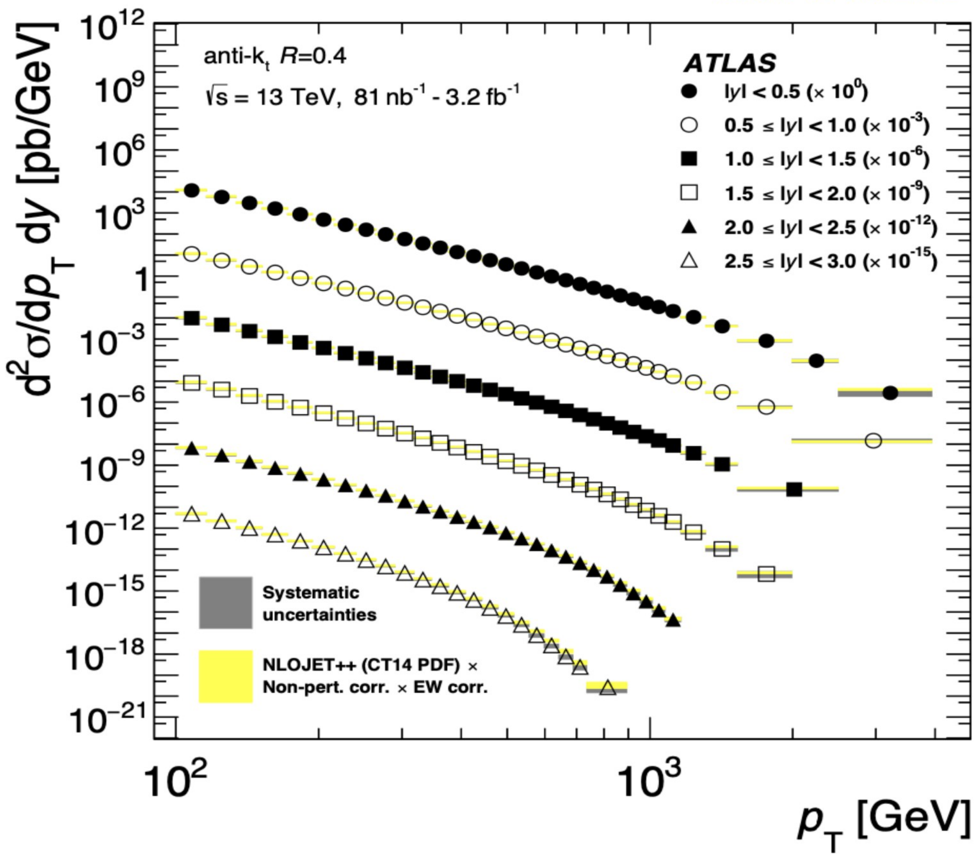
JETM-2022-005



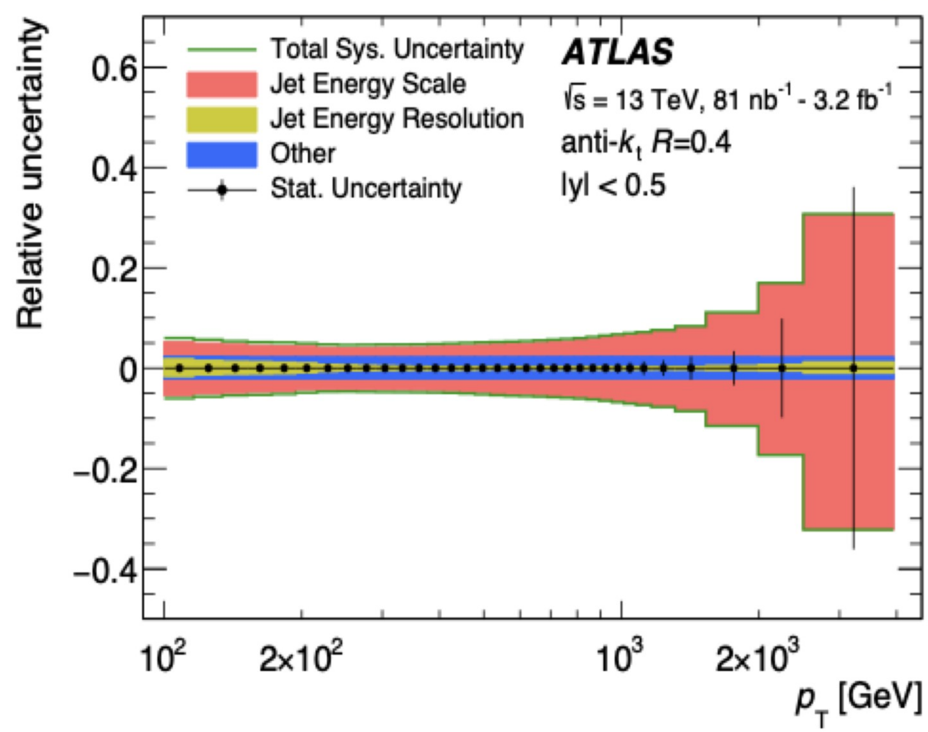
An analysis example: jet cross-section measurements

- The latest ATLAS inclusive jet and di-jet cross section measurement was performed using the 2015 data collected covering the p_T range from 100 GeV to 3.5 TeV
- Topocluster jets reconstructed with anti-k_t R=0.4 jets were used
- The main uncertainties for this analysis comes from the jet calibration
  - **Improvements in the jet collection and flavour uncertainties will be very beneficial for this analysis! And for many others...**

ArXiV: 1711.02692



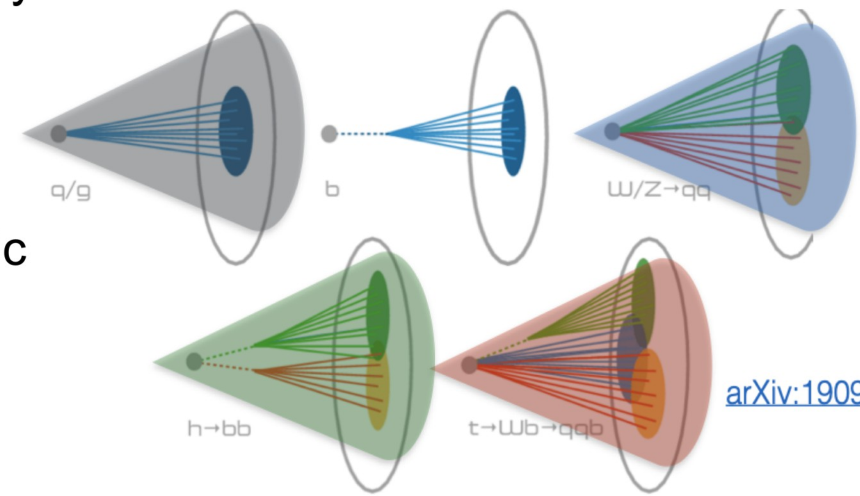
ArXiV: 1711.02692



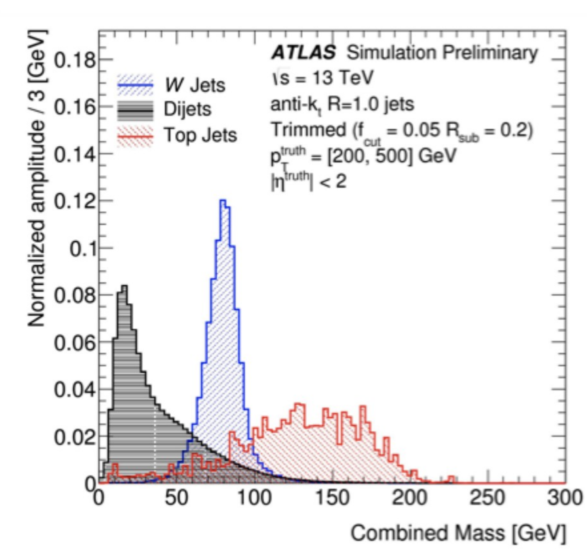
(a) inclusive jet

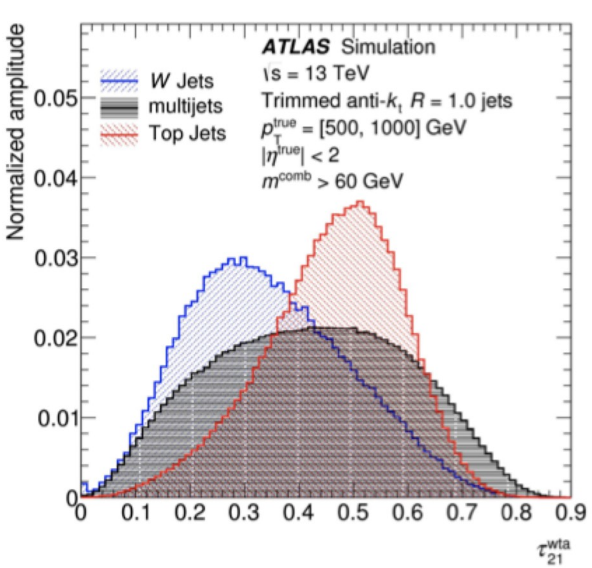
Jet tagging

- **What is the origin of a given jet?** Is it coming from a gluon or a quark? Could it be from an hadronically decaying W/Z/Higgs boson or a top with a high Lorentz boost?
- ATLAS has developed **several kind of taggers** in the last years taking advantage of the characteristic **internal substructure of the jets depending on their origin**
- Searches and measurements at the LHC are probing progressively higher energy regimes and they benefit a lot from these taggers for high p_T jets



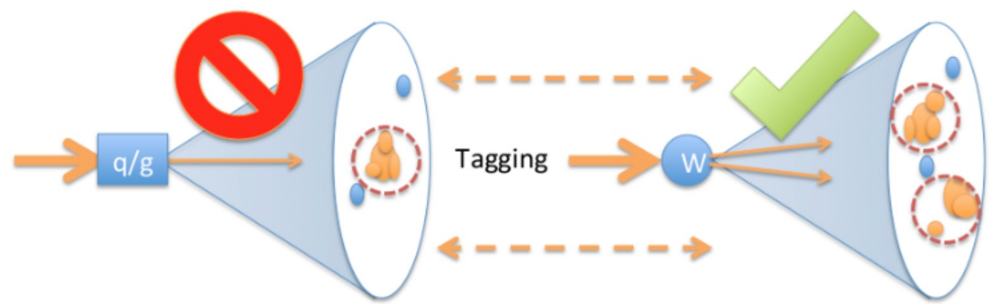
arXiv:1909.12285





Jet tagging

- Let's focus on the case of discriminating between **W/Z/H/top vs QCD jet**
- **Many multivariate taggers being used at the moment with good performance**
  - First taggers used high level features (e.g energy correlators)
  - Modern taggers use low level inputs (4-vector information)



H→bb vs QCD tagging, making extensive use of tracking and vertexing information

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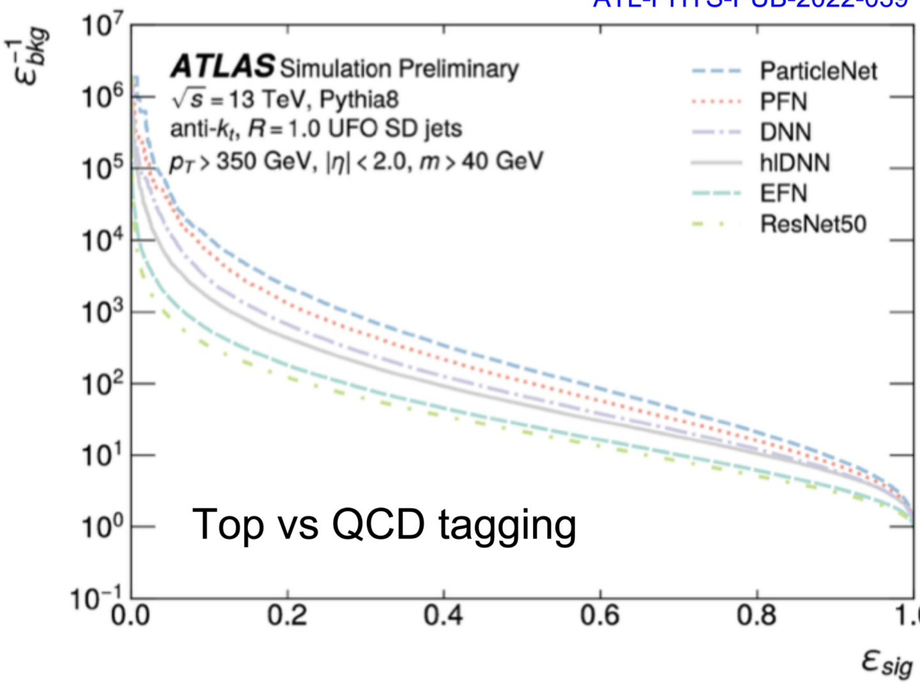

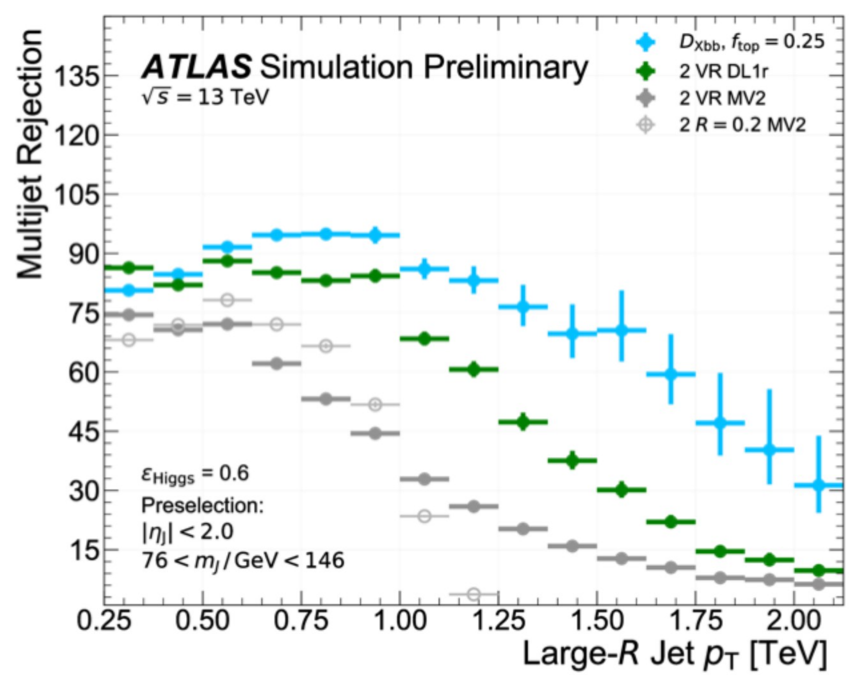

Jet tagging: how do we calibrate the taggers?

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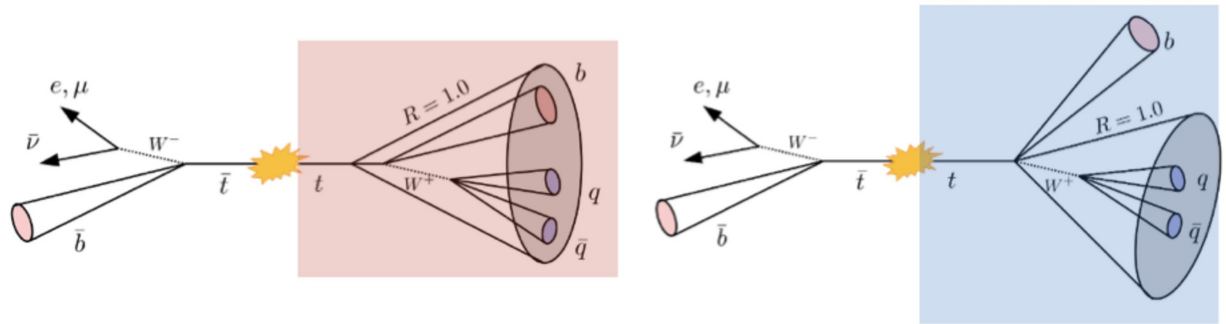
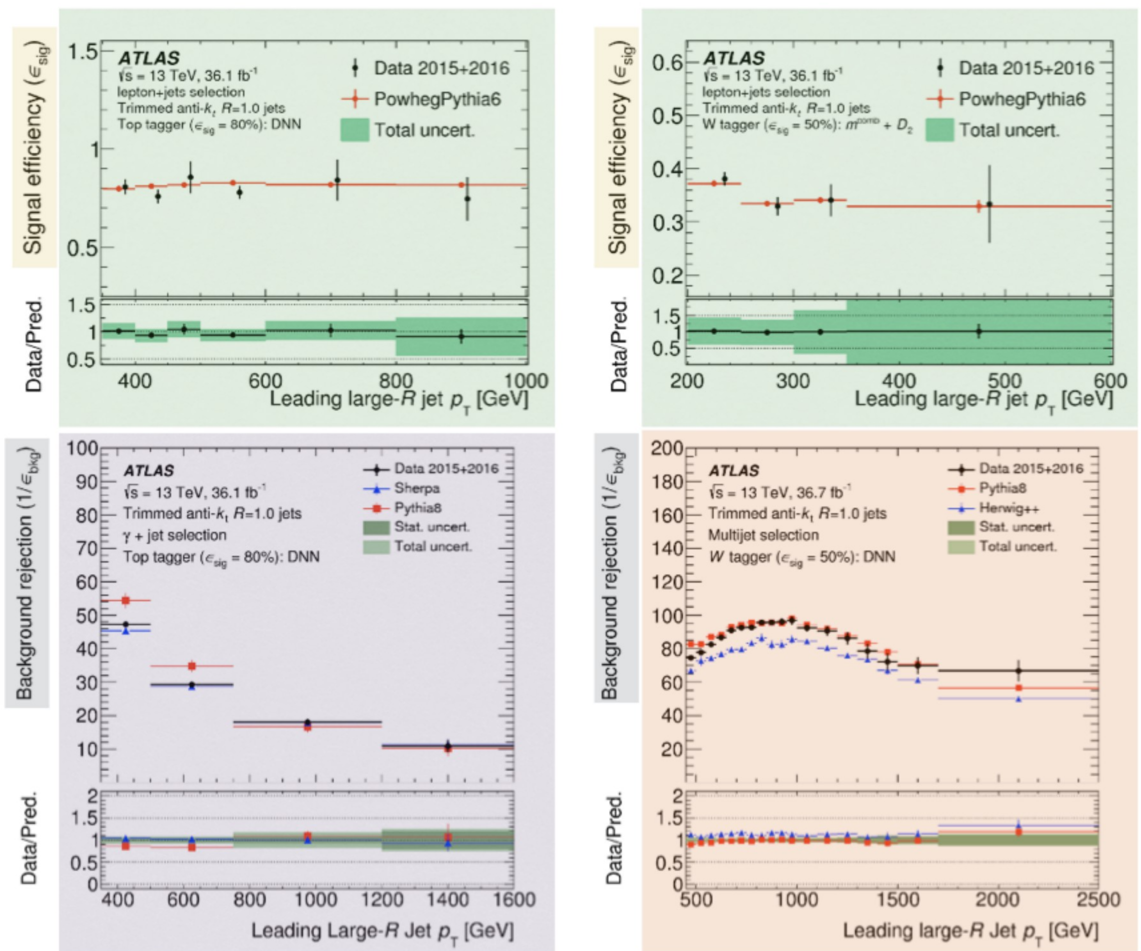
- **Correct the tagger efficiency in MC to match the one in data**
- **For W/top taggers**
  - Primarily look at top-antitop events for signal calibration
  - Dijet and photon+jet samples used for calibrating background rejection
- **For H→bb taggers:**
  - Z/gamma+jets for the signal
  - Top-antitop and g→bb for background



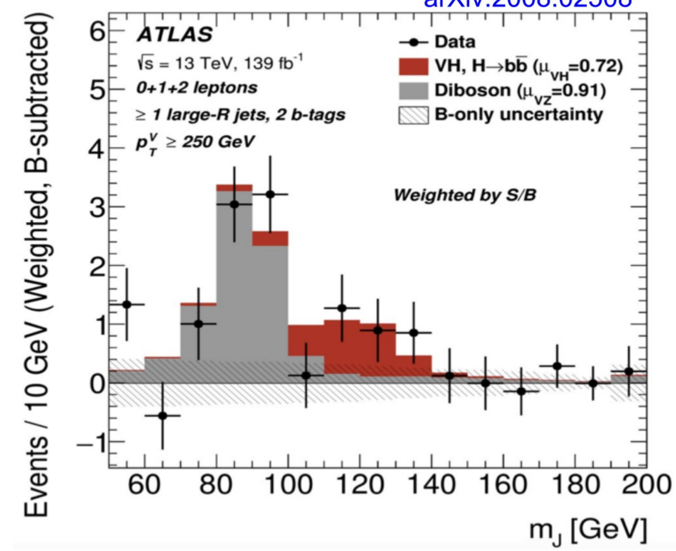


Taken from Brian Le

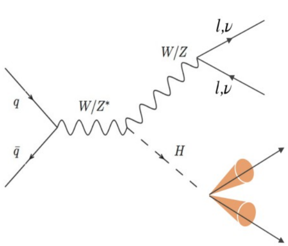
An analysis example: boosted H→bb

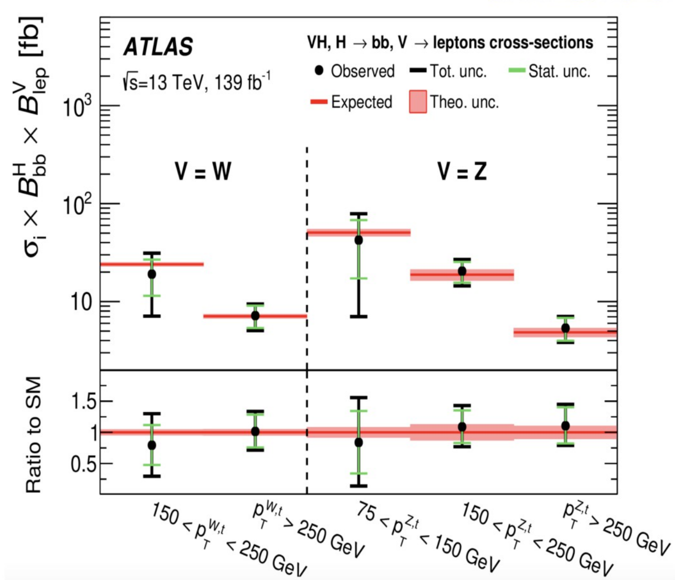
- Signal-to-background ratio increases with Higgs boson p_T
- Focus on the **VH, H→bb and V→leptons** final state
- The use of **boosted H→taggers allowed to reach higher transverse momentum** and their combination increase the precision and knowledge of this channel (ATLAS-CONF-2021-051)

arXiv:2008.02508

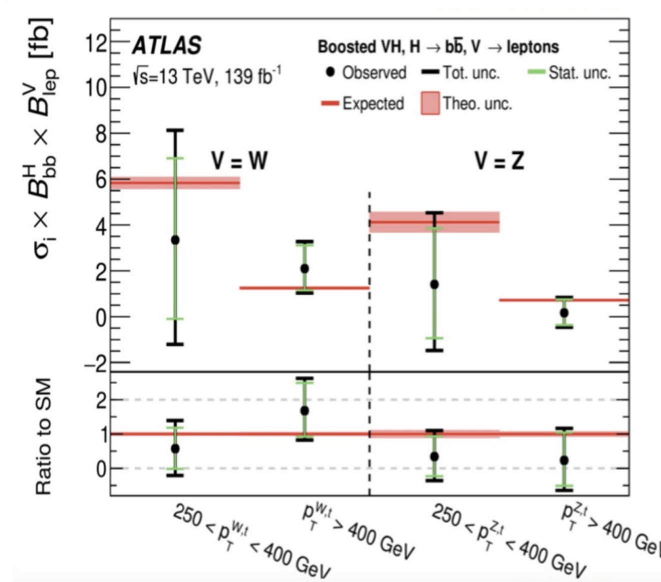


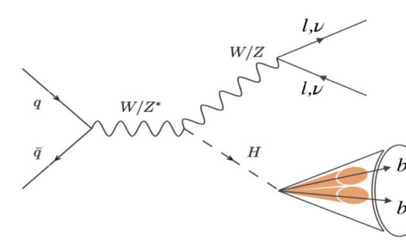
arXiv:2007.02873





arXiv:2008.02508





Summarising

- Jet reconstruction, calibration and tagging important for a more precise physics in the ATLAS experiment

- Great deal of improvements in the jets world during Run-2 and the LS2
  - Evolution of reconstruction algorithms from Topoclusters (Calorimeter-only) to Pflow and UFO (tracking+calorimeter)
  - Percent-level uncertainties across wide kinematic range for the jets calibration
  - Boosted jet tagging constantly improving discrimination

- Also showed the direct impact of the work on jet performance on the analysis
  - The success of an HEP experiment relies not only on the analysis design but on detector operations and performance work

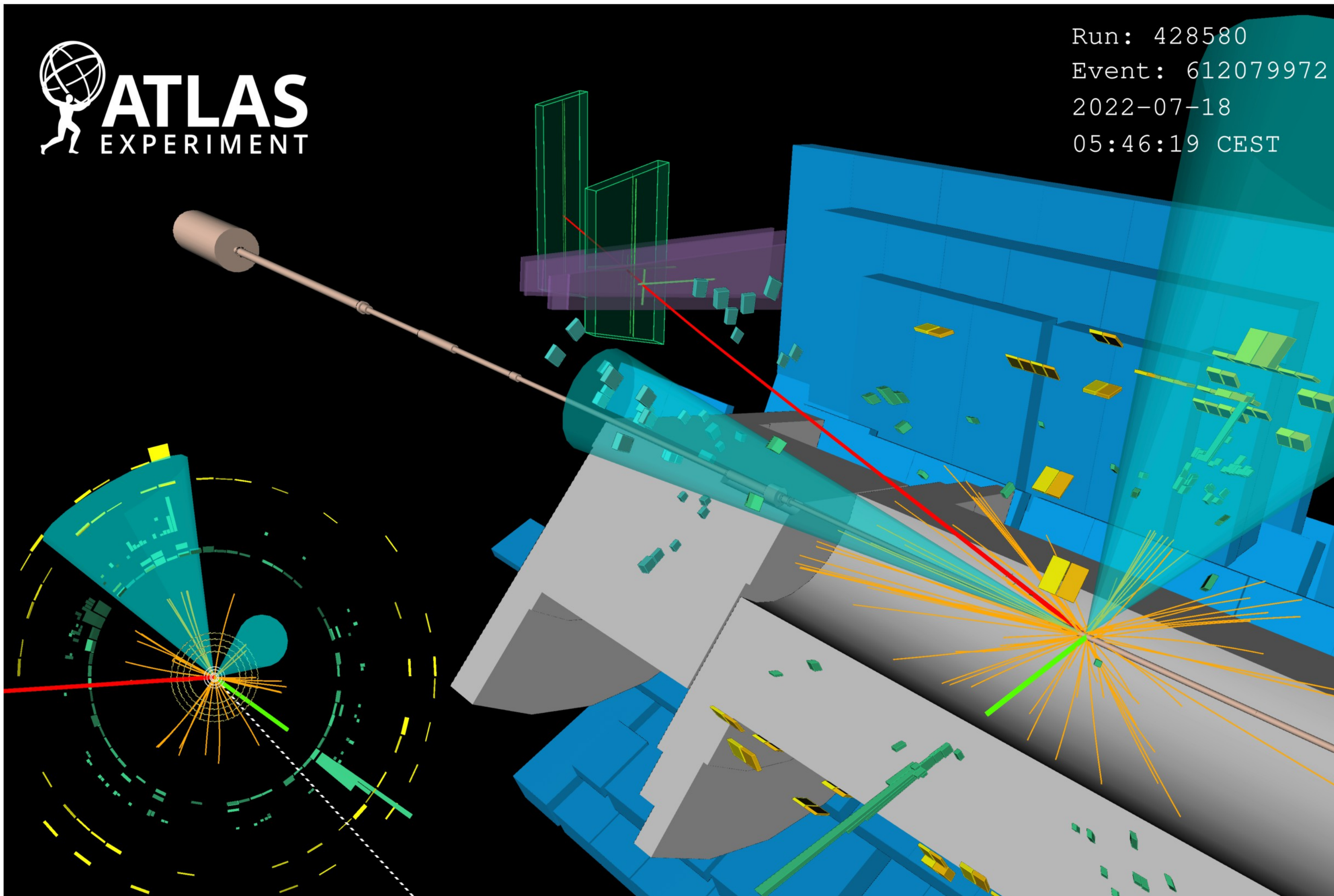
- Run 3 brings more luminosity at slightly higher energy but to do better than 1/√luminosity we need to bring new strategies to improve the uncertainties

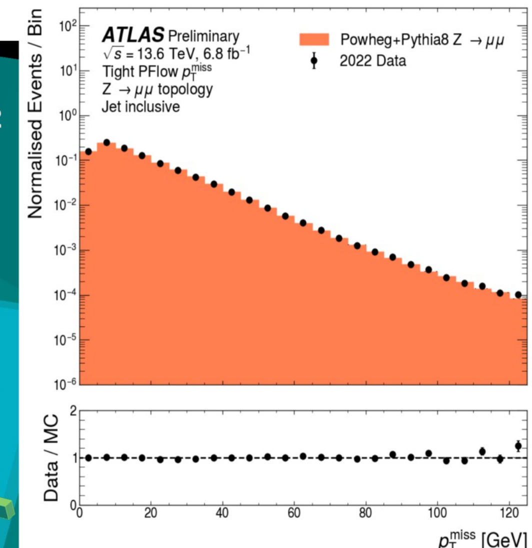
  - Lots of work ongoing in that direction, stay tuned!

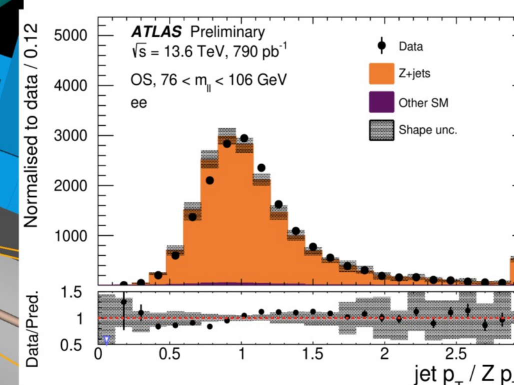
Run-3 just started

The LHC and ATLAS

- And with it plenty of opportunities opened, more jets and more fun physics
- Looking already at early Run-3 data!







BACKUP