Forward jets at the ATLAS detector

A Mismodelling Mystery

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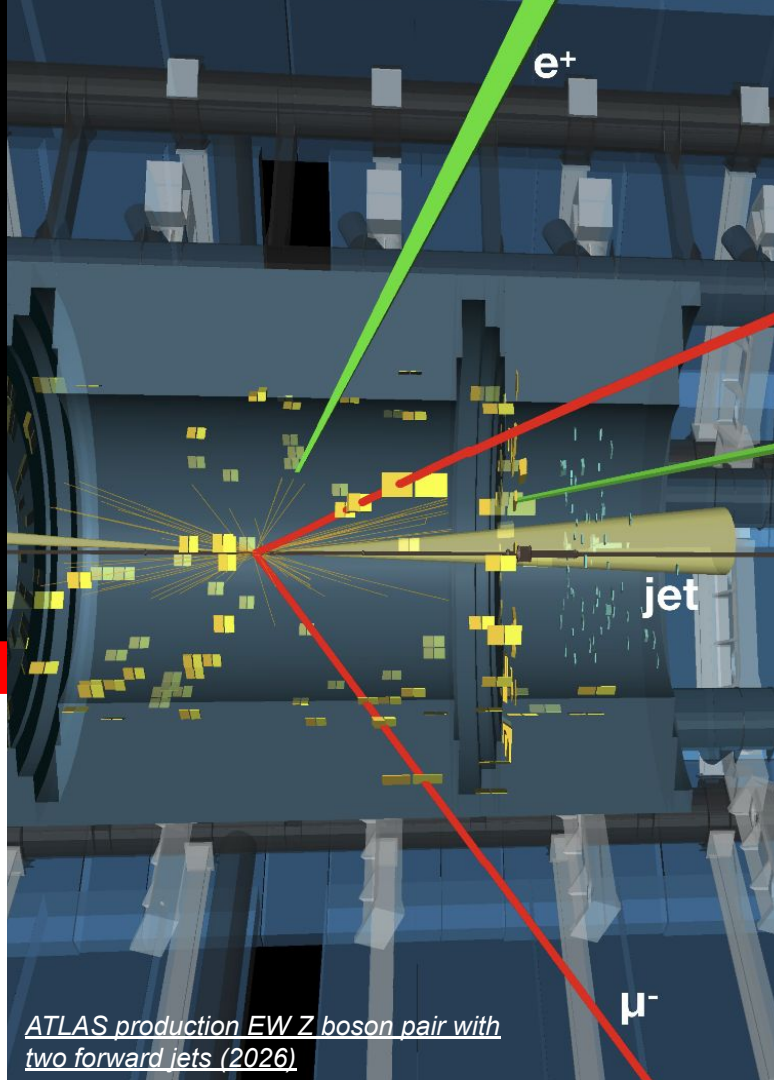
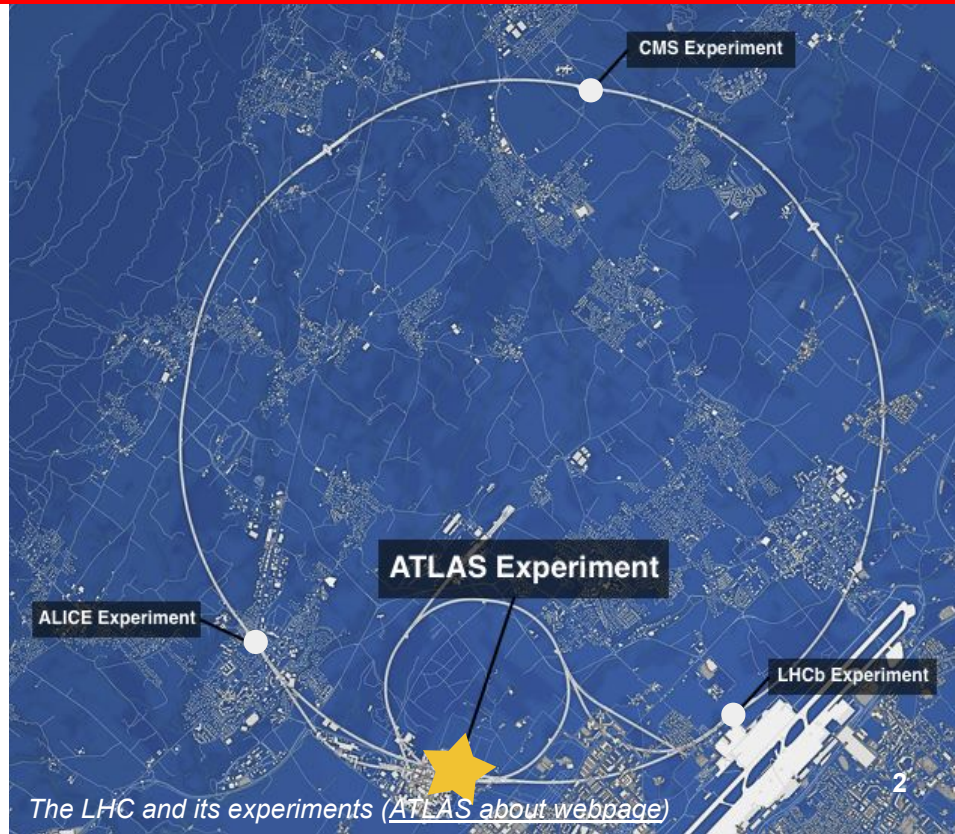
ATLAS Carleton



ATLAS production EW Z boson pair with two forward jets (2026)

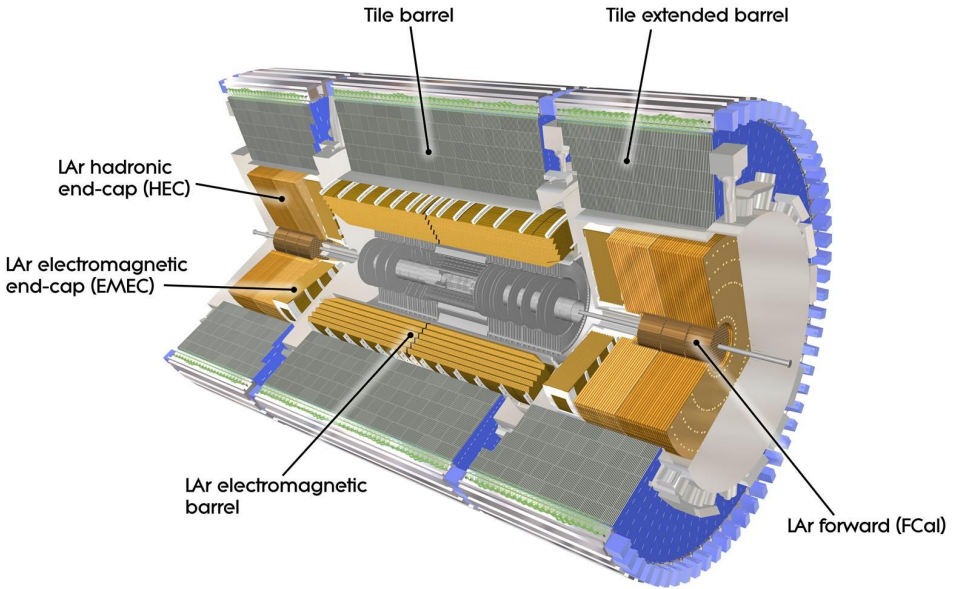
The Large Hadron Collider & The ATLAS Experiment

- LHC
  - Located at CERN, Geneva
  - Proton - proton collider
  - Collision energy of 13.6TeV
  - Collisions happen every 25 ns
    - Some are high energy
    - Most are low energy that we aren't interested in (pileup)
- ATLAS Experiment
  - Located on the LHC 100m underground
  - "A big camera"
  - Data taking periods
    - Run 1 (2009-2013)
    - Run 2 (2015-2018)
    - **Run 3 (2022-2026)**



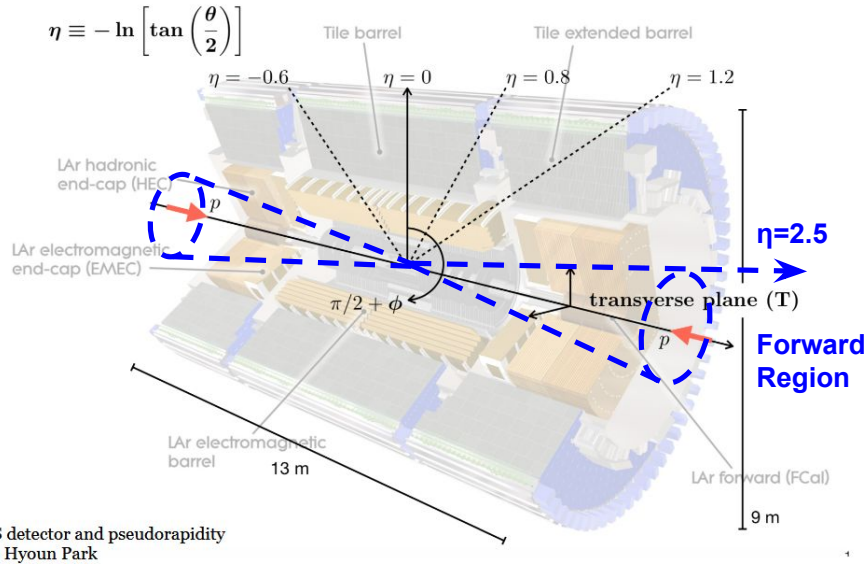
The LHC and its experiments (ATLAS about webpage)

ATLAS detector and the forward region



ATLAS detector and the forward region

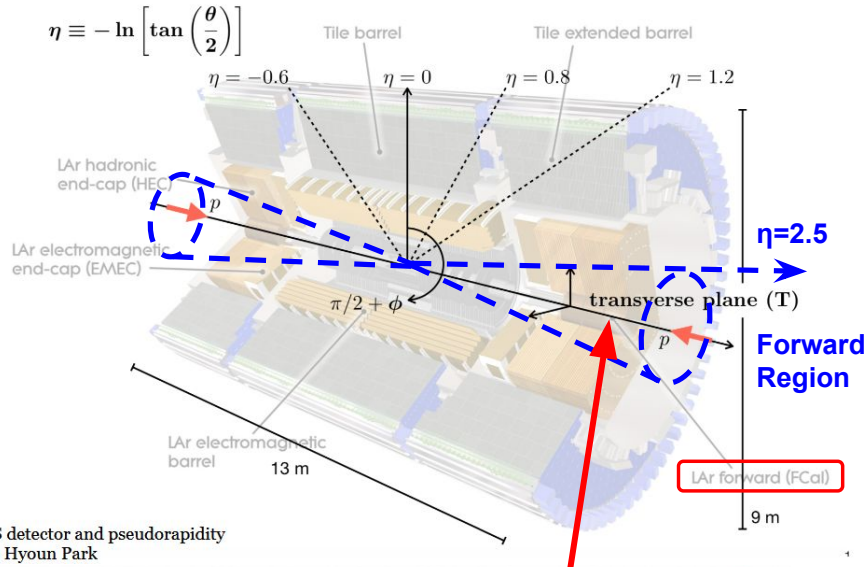
- η - pseudorapidity
  - quantifies the angle relative to the beam line
- ATLAS forward region
  - 2.5<|η|<4.5
  - Particles in this region are travelling close to the beam line



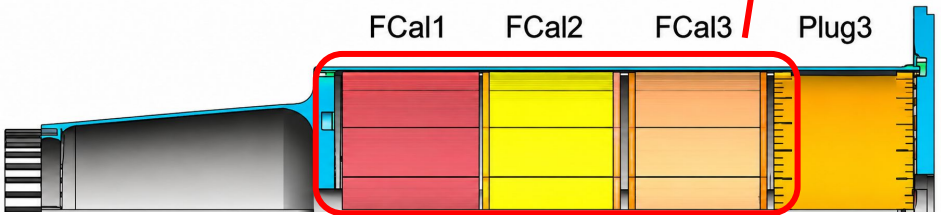
The ATLAS detector and pseudorapidity
Credit: Tae Hyoun Park

ATLAS detector and the forward region

- η - pseudorapidity
  - quantifies the angle relative to the beam line
- ATLAS forward region
  - 2.5<|η|<4.9
  - Particles in this region are travelling close to the beam line
- Major sub detector in the forward region is the Forward Calorimeters (FCals)
  - 3.2 < |η| < 4.9
  - 3 FCal components
    - FCal 1 EM Calo (Cu absorber)
    - FCal 2 Hadronic Calo (W absorber)
    - FCal 3 Hadronic Calo (W absorber)

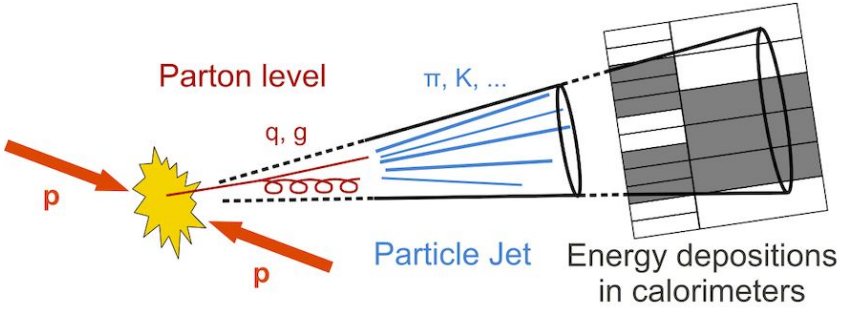


The ATLAS detector and pseudorapidity
Credit: Tae Hyoun Park

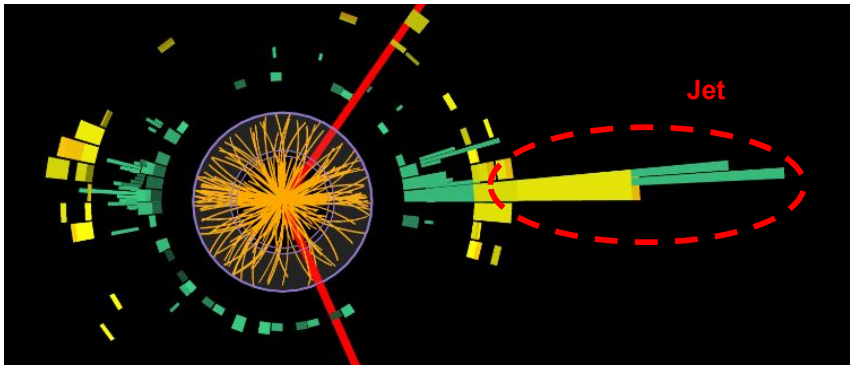


Hadronic jets

- Collisions often produce high energy streams of low mass particles
  - These are called **jets**
- ATLAS reconstructs jets using energy deposited in calorimeters
  - Energy deposited via showering
- High energy jets can be signatures for specific physics phenomena
  - e.g: Vector Boson Fusion produces a jet pair near the beam line



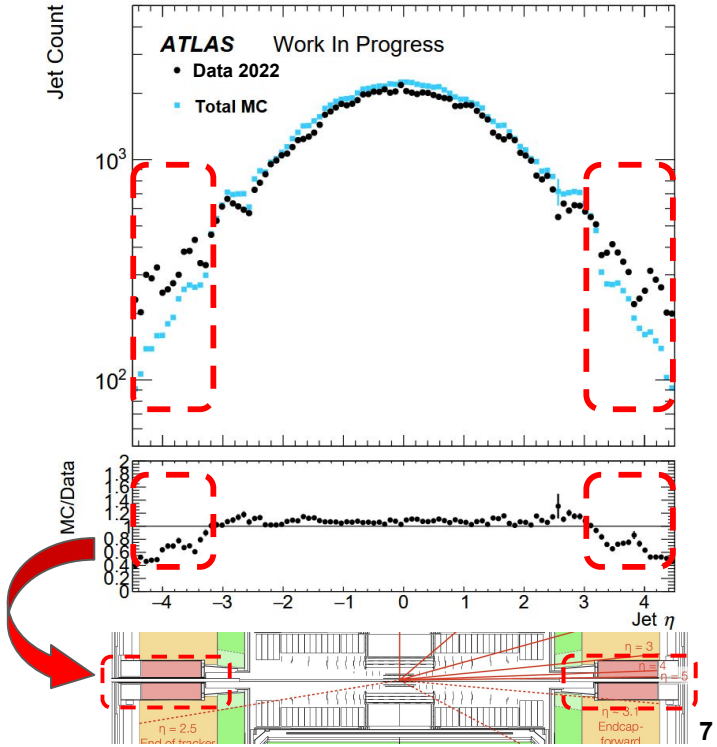
(Above) p-p collision → quark → hadronic jet → measured jet
(Below) Image of ATLAS detector readout of an event with a jet (2015)



Jet mismodelling in the forward region

- ATLAS develops Monte Carlo (MC) programs to provide predictions of data
  - These simulation are generally quite accurate
- Run 3 (2022) MC clearly underpredicts number of jets in the forward region
  - At |η|>3.2 there is a deviation as high as ~50%!
    - That is where the FCal is located!
- Run 2 (2015-2018) data and MC did not have this disagreement

Why do we see this in Run 3?



2022 data & MC for jet rapidity within ATLAS. The underpredicting region corresponds with the forward calorimeter

What could it be?

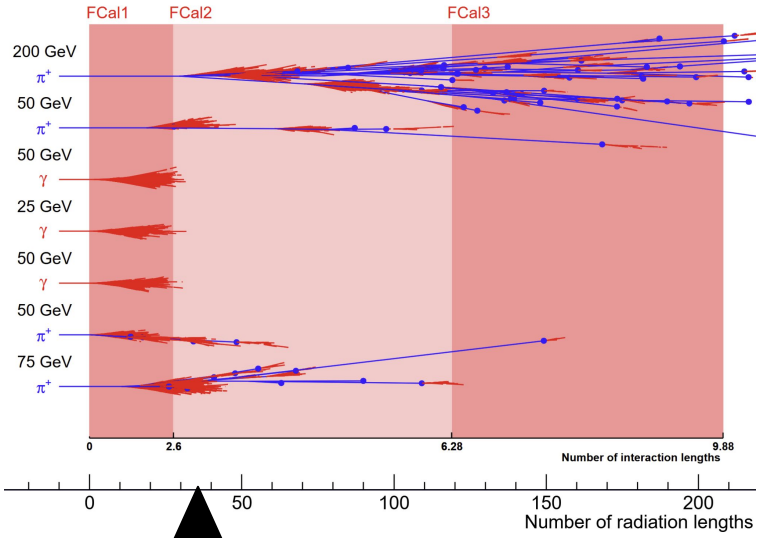
Noise or pileup in the data? ✗

Event simulation? ✗

Detector energy response simulation? ✓

Simulation of jets in the forward calorimeter

- High energy particles hitting the FCal produce particle showers
  - EM showering (e, γ)
  - Hadronic showering (π, p, K, …)
- GEANT4 simulates the showering and energy deposition
  - Changes made to GEANT4 seem to have impacted showering in dense materials
  - FCal 2 and 3 are **very dense**!
    - **Tungsten (W)**

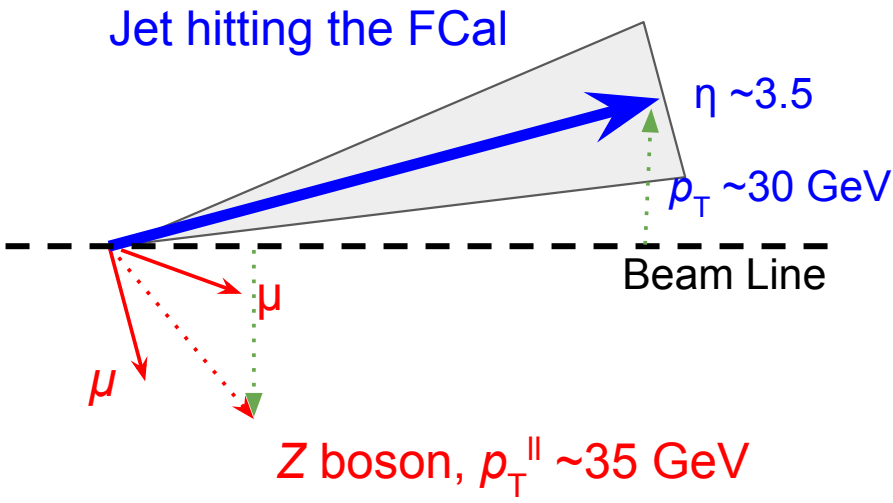


Simulated showers deposit less energy → Simulated jets are reconstructed with a lower energy → After energy threshold we see less jets in MC

Example of a shower occurring within the FCal as a ~500 GeV jet enters

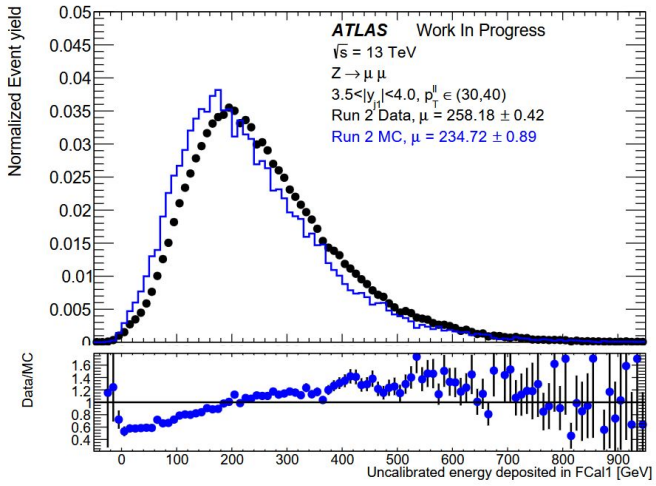
Examining the jet energy in the FCal with Z + jet

- Examined the jet energy deposited in the FCals using jet and Z boson events (MC and Data)
  - Z bosons are easy to identify
  - Accompanying jet is often high energy
  - The jet and Z boson will have balanced transverse momentum
    - We can predict jet energy
- Energy examination
  - Select region in the FCal (3.5>|η|>4.0)
  - The energy deposited in data and MC will be measured and studied

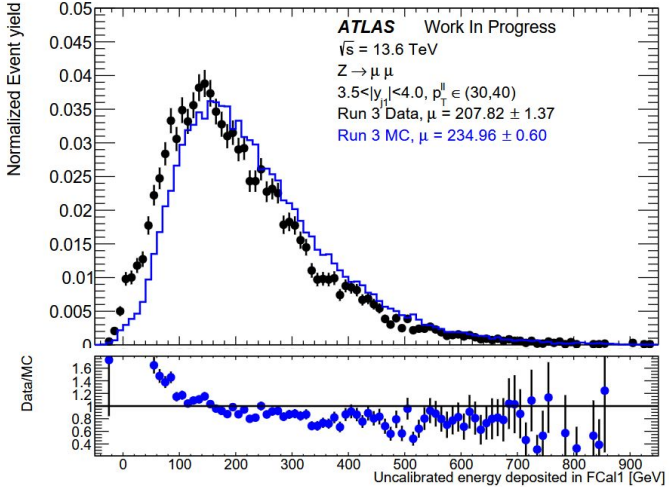


Energy deposition in FCal 1 for Run 2 and Run 3

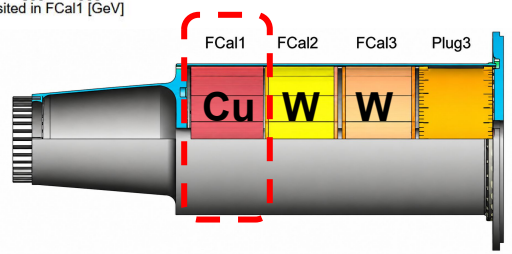
Run 2 (2018)



Run 3 (2022)

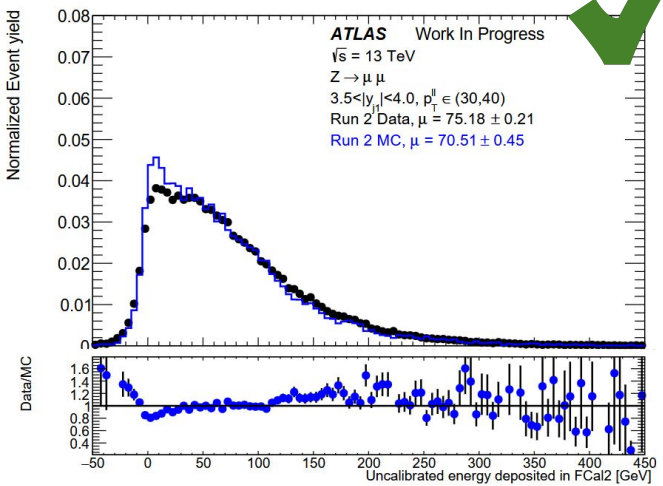


Energy deposited in FCal 1 by jets in Run 2 and Run 3 data and simulation

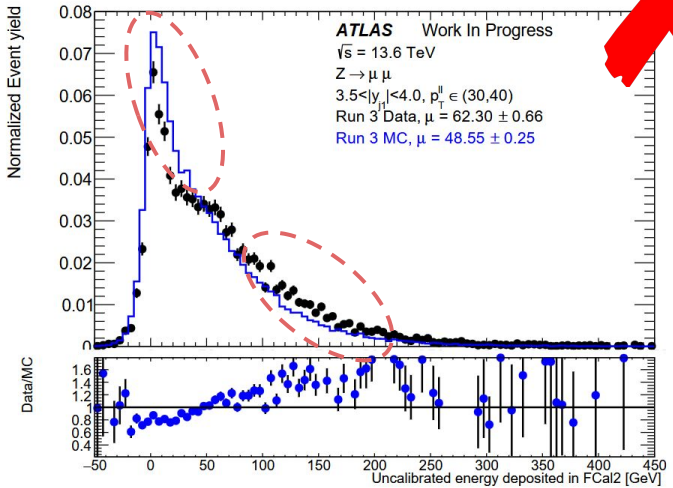


Energy deposition in FCal 2 for Run 2 and Run 3

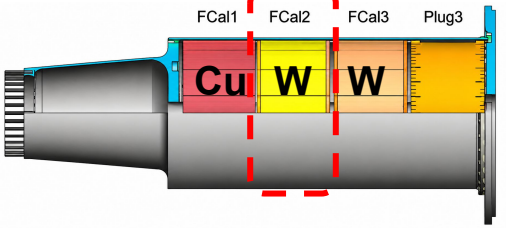
Run 2 (2018)



Run 3 (2022)

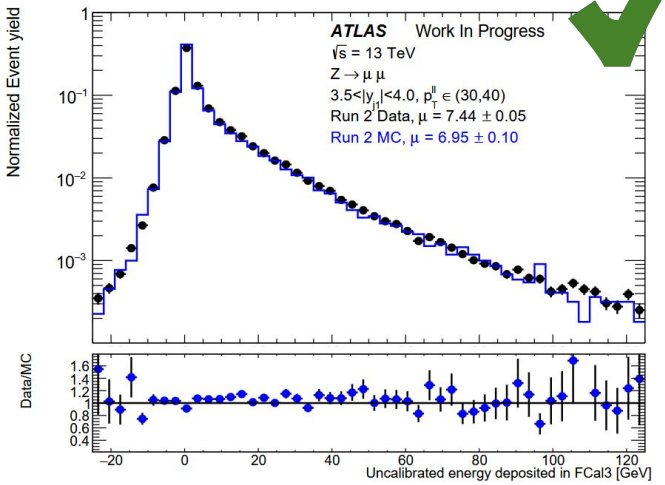


Energy deposited in FCal 2 by jets in Run 2 and Run 3 data and simulation

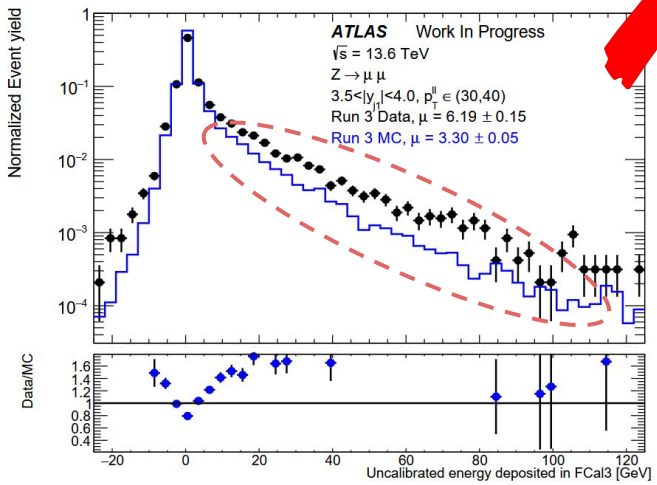


Energy deposition in FCal 3 for Run 2 and Run 3

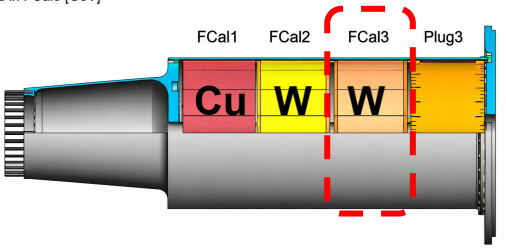
Run 2 (2018)



Run 3 (2022)



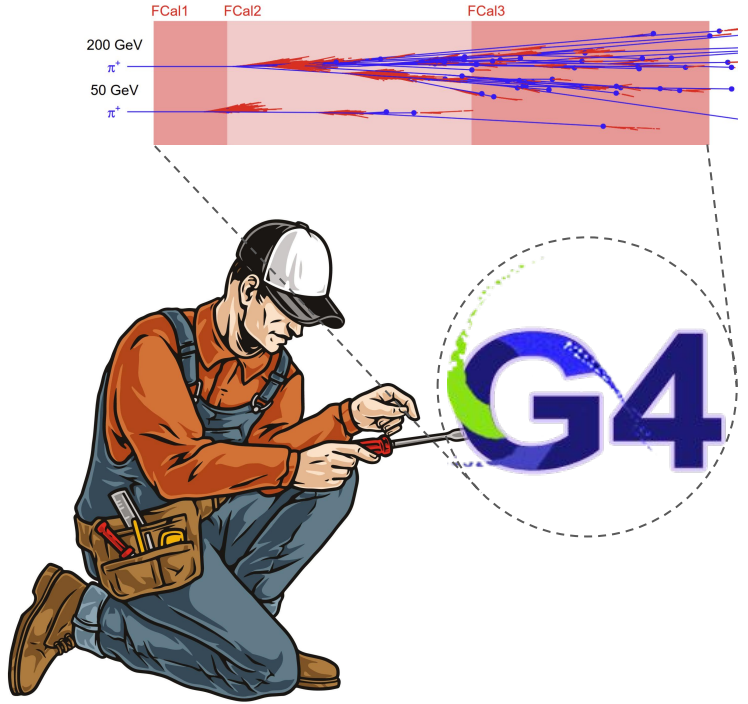
Energy deposited in FCal 3 by jets in Run 2 and Run 3 data and simulation



Patching GEANT4

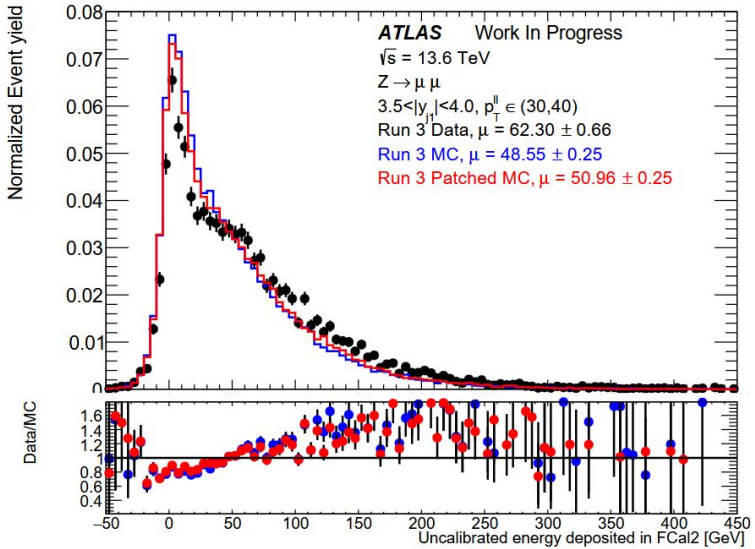
- In Run 3 (2022) there is an issue modelling the energy deposited into FCal 2 & FCal 3
  - Changes made to GEANT4 are impacting showering in dense materials (Tungsten)
- ATLAS simulation group is patching GEANT4 to fix this issue
- The latest patch:
  - Set cascade and string models to match Run 2
  - Expected to recover ½ to ⅔ of what was lost

Let's see if it works!

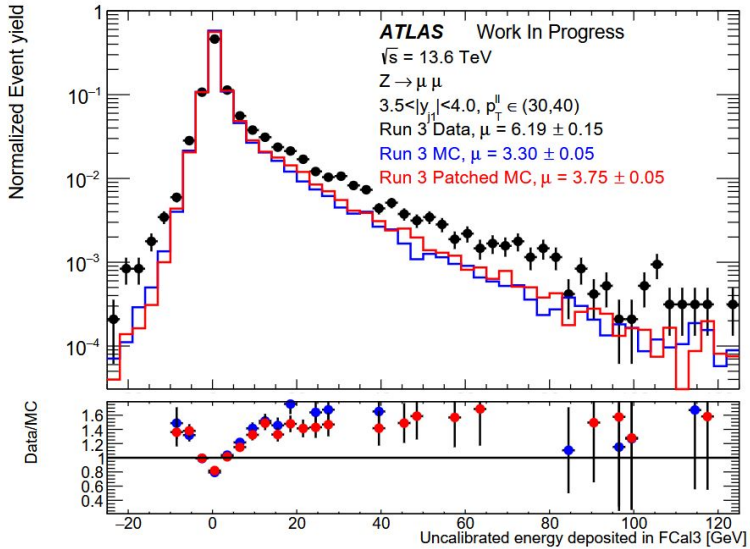


Does the patch work?

FCal 2 (W hadronic calo)



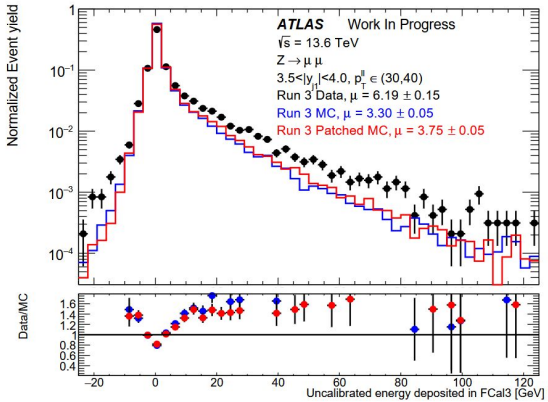
FCal 3 (W hadronic calo)



- Small improvement in the patched MC from the current MC in FCal 2 and FCal 3
  - Not as good as expected → does **NOT** fix the issue
- More patches to come!

Conclusion & the future

- **Issues** observed in detector simulation of **forward region**
  - Only for ATLAS Run 3 (2022–2026) simulation
  - Lower energy response → fewer jets predicted by simulation
  - Believed due to new ATLAS GEANT4 settings used for Run 3:
    - Improved response in copper absorbers (central region)
    - Appears **significantly worse in dense materials** (FCal 2+3)
  - A dedicated jet calibration with increased uncertainty is applied as preliminary fix
- I'm working with ATLAS simulation group to examine this
  - Two patches to GEANT4 10.6 have been checked
    - The impact of these patches have been insufficient
  - **More GEANT patches are being produced!**
    - Changing other properties of the GEANT4 detector simulation

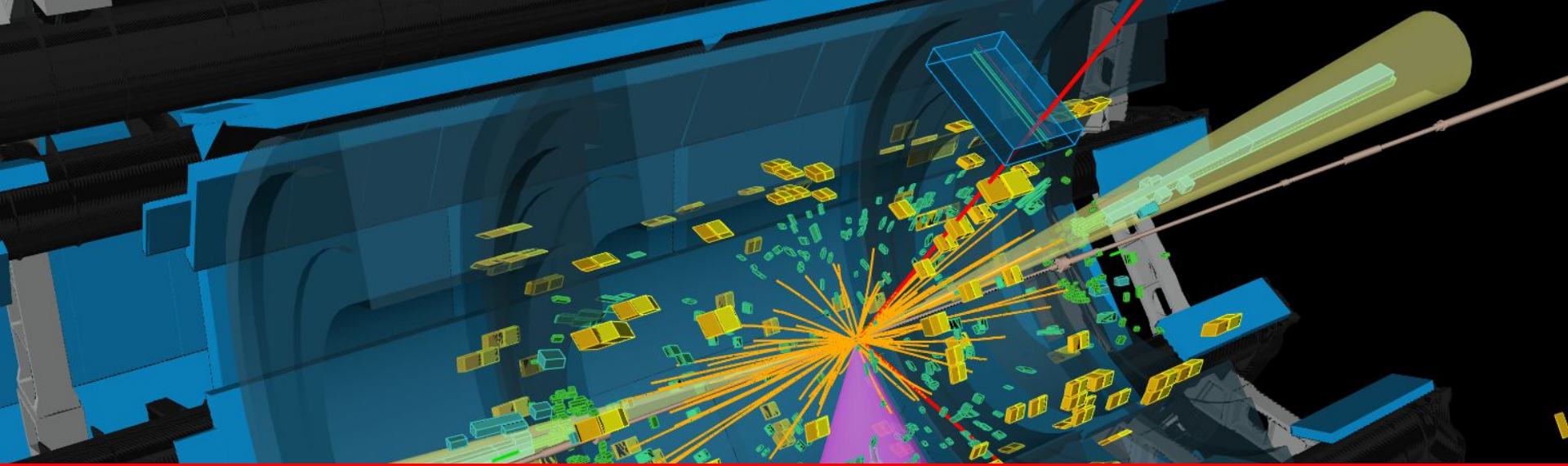


Run 3 (2022) data, MC, and patched MC in FCal 3

ACTIVE INVESTIGATION

It is important for ATLAS analyses to have an accurate modelling of forward hadronic activity (jets!)

This impacts many analyses (Higgs, VBF, HI ...)



Thank you!

ATLAS H→Z gamma event from 2024
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGP-2024-19/

Backup slides

What could it be?

Noise or pileup in the data?

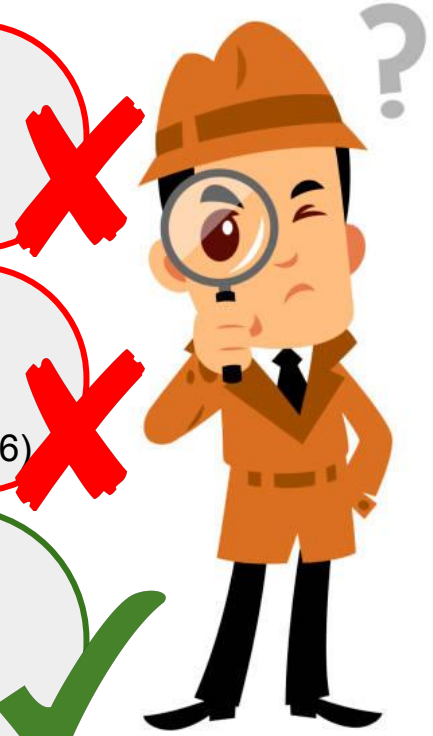
- **Maybe:** Excess jets in data are due to more pileup then we expect
  - Jets reconstructed from pileup have low energy
- **But:** Discrepancy is not only for low energy jets

MC event modeling?

- **Maybe:** A change in particle production simulation can account for the MC underpredicting
- **But:** No major changes between Run 2 (2015-2018) and Run 3 (2022-2026)

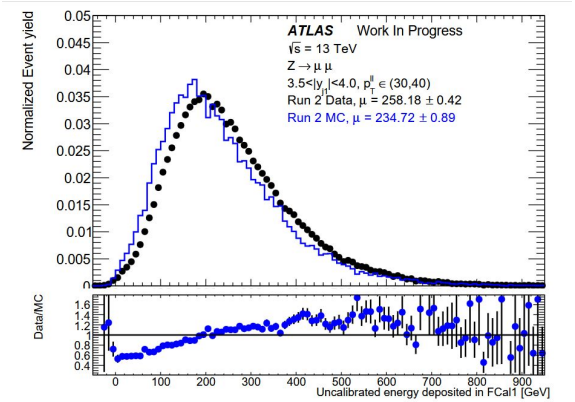
Detector simulation?

- **Maybe:** A change in the simulation of the detector energy response could affect the predicted number of jets
- **This is consistent with our observations!**
  - Detector simulation software changed between Run 2 and Run 3

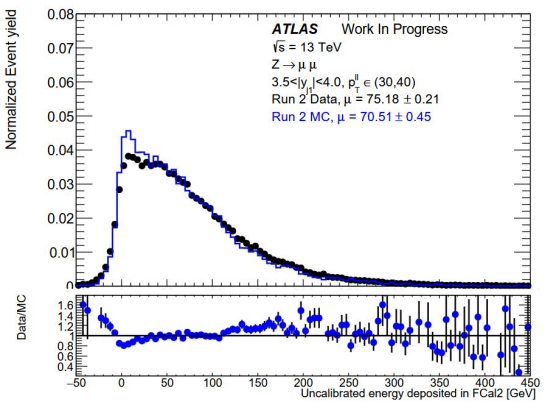


Energy deposition Run 2

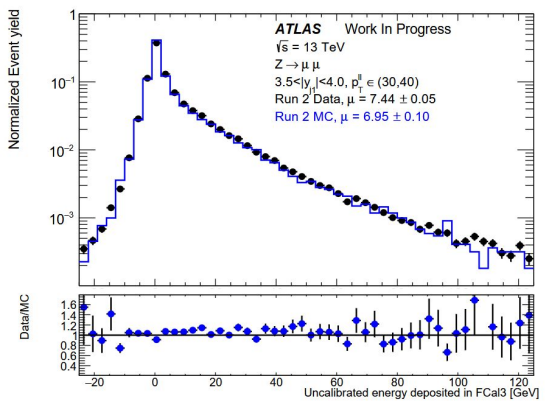
FCal 1 (Cu EM calo)



FCal 2 (W hadronic calo)



FCal 3 (W hadronic calo)

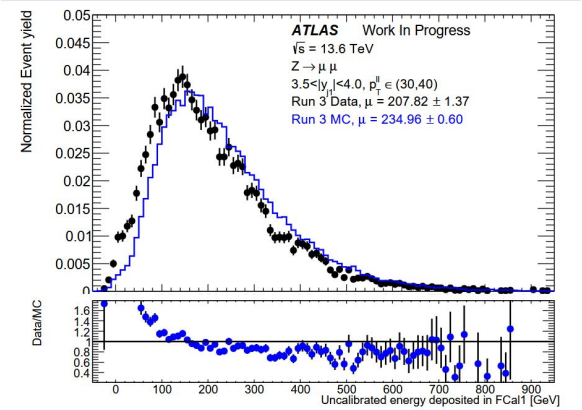


As a baseline let's examine the energy deposited in the FCals using data and MC from Run 2.

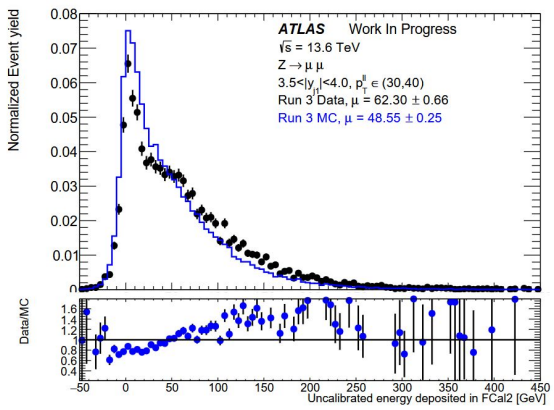
Hadronic calorimeters have good modelling but the EM calorimeter modelling is a little weak.

Energy deposition Run 3

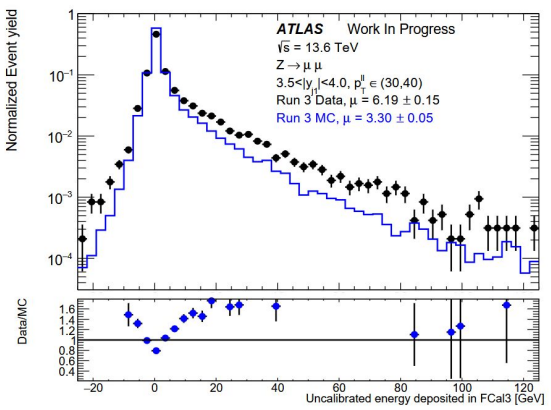
FCal 1 (Cu EM calo)



FCal 2 (W hadronic calo)



FCal 3 (W hadronic calo)

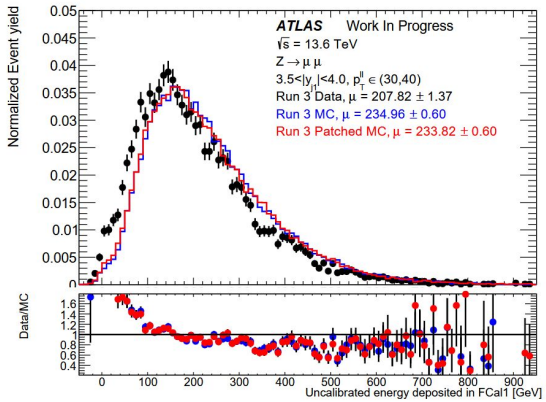


Now let's examine the energy deposited in the FCals using data and MC from Run 3.

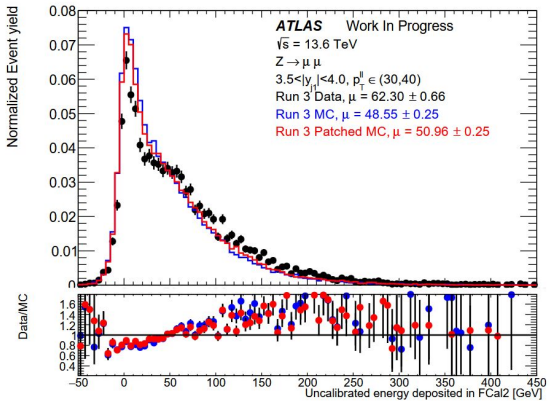
EM calorimeter modelling has stayed similar but the modelling of the hadronic calorimeters has greatly degraded.

Energy deposition Run 3 with a GEANT4 patch

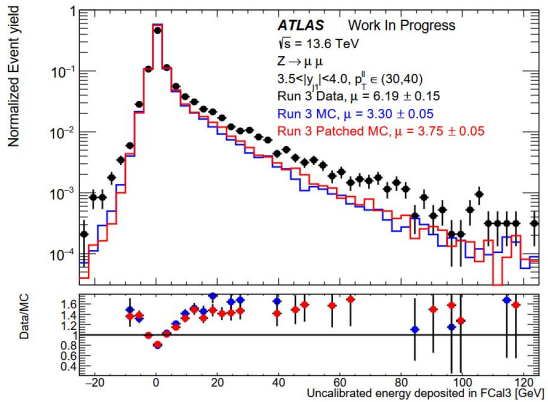
FCal 1 (Cu EM calo)



FCal 2 (W hadronic calo)



FCal 3 (W hadronic calo)



- We see a small improvement in the patched MC from the current MC in FCal 2 and FCal 3
  - Not as good as expected
  - Does **NOT** fix the issue
- More patches to come!

Mean Energy deposition (Run 2 and Run 3)

Summary of the mean energy deposited in each forward calorimeter as seen in plots using data and MC from Run 2 and Run 3

	FCal1 (GeV)	FCal2 (GeV)	FCal3 (GeV)
Data Run 2	258.18 ± 0.42	75.18 ± 0.21	7.44 ± 0.05
MC Run 2	234.72 ± 0.89 (-9%)	70.51 ± 0.45 (-6%)	6.95 ± 0.10 (-7%)
Data Run 3	207.82 ± 1.37	62.30 ± 0.66	6.19 ± 0.15
MC Run 3	234.96 ± 0.60 (+13%)	48.55 ± 0.25 (-22%)	3.30 ± 0.05 (-47%)
MC Run 3 Patched	233.82 ± 0.60 (+13%)	50.96 ± 0.25 (-18%)	3.75 ± 0.05 (-39%)

Run 3 MC does not match data as well as Run 2 did