Performance of hadronic shower measurement with LHCf and ATLAS ZDC detectors

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1. Introduction

It is important to understand high energy hadronic interactions in order to simulate air shower development induced by ultra-high energy cosmic rays (UHECRs). The knowledge of high energy hadronic interactions is essential to improve chemical composition measurement of UHECRs and to solve the muon puzzle.

The LHC forward (LHCf) experiment measures neutrons and photons produced in the very forward region of pp collisions at LHC. The performance of hadronic showers induced by neutrons, especially energy resolution, is important to measure

- neutrons generated by one-pion-excahnge,
- neutrons generated by Λ decay, and
- inelasticity by leading neutron measurement.

Additionally, uniformity of the performance is important because the neutron differential cross section for a pseudo rapidity region and the transverse momentum of the particle etc. can be determined.

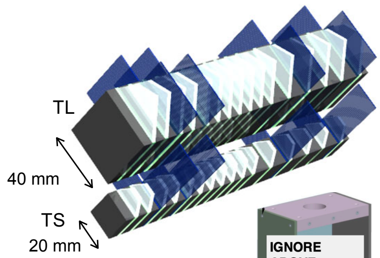
LHCf + ATLAS ZDC analysis

LHCf has a poor energy resolution of 40% for neutrons because of the leakage of developed shower particles. Therefore a joint operation of LHCf with ATLAS ZDC installed behind of LHCf has been performed in 2022. In this poster, we present the performance of LHCf + ATLAS ZDC joint operation studied by a beam test at SPS.

2. Setup of LHCf+ATLAS-ZDC measurement

LHCf detector (Arm 1)

Size : 620mmH x 91mmW x 280mmT
Transverse size of calorimeters:
20x20mm (TS) and 40x40mm (TL)
Calorimeters:
Tungsten (total length 44 r.l. and 1.7 λi)
16 GSO scintillator layers
Position sensitive layer:
GSO bar XY hodoscopes at 6,10,32,42 r,l
Energy resolution for neutrons : 40%



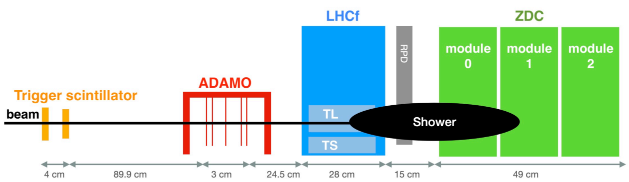
ATLAS ZDC detector

3 ZDC-HAD modules were used.
Size of a single module : 600mmH x 90mmW x 154mmT
Sandwich of Tungsten plate (10mm) and fused-silica fibers (Φ=1.5mm)
Readout
Cherenkov lights in the fibers by a single PMT in each module
Total interaction length : 3.4 λi

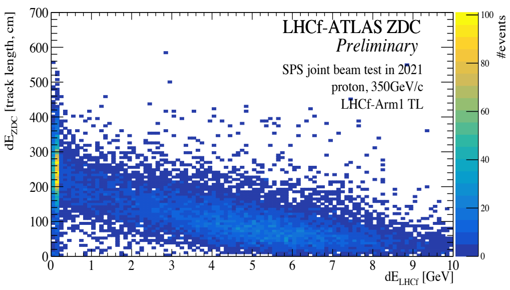
The detector is normally used for operations with LHC ion collisions.
It was exceptionally installed for a special low-luminosity run with pp collisions in 2022 for this joint operation with LHCf.

Beam test at SPS

- September 2021 at SPS T2-H4 beam line
- Beams
  - 350 GeV/c proton for resolution studies.
  - 100 and 200 GeV/c electron beams for detector calibration
- Statistics
  - 8.6 M events with protons, and 12.2 M events with e⁻
- The detectors were aligned among the beam line.
  The ZDC-HAD modules were installed as the LHC operation configuration.



3. Correlation of dE in LHCf and ATLAS ZDC



Negative liner correlation between energy deposit of LHCf and ATLAS ZDC

4. Reconstruction method

An energy estimator E_{est} is defined as

$$E_{est} = dE_{LHCf} + \alpha\, dE_{ZDC}\ ,$$

where α is a scale factor, which is defined from the slope of correlation between E_{LHCf} and E_{ZDC}. Then the reconstructed energy E_{rec} is estimated as

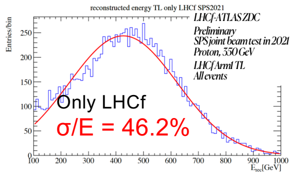
$$E_{rec} = F(E_{est})\ ,$$

where F is a quadratic function defined using a MC simulation.

The XY position of the shower cores are measured by the GSO bar XY hodoscopes of LHCf Arm1.

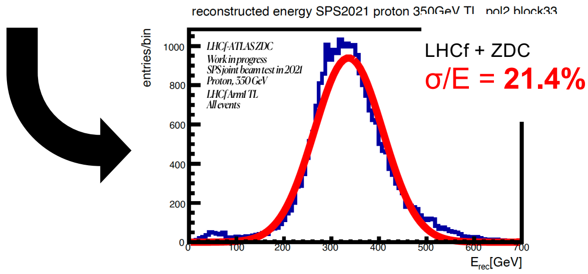
5. Result

Energy resolution



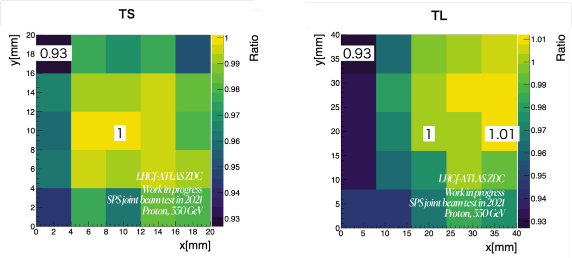
Condition
- 350 GeV proton beam
- The center region (8x8 mm²) of TL

The energy resolution of neutron measurement improved from 46.2% to 21.4% by LHCf + ATLAS ZDC joint analysis



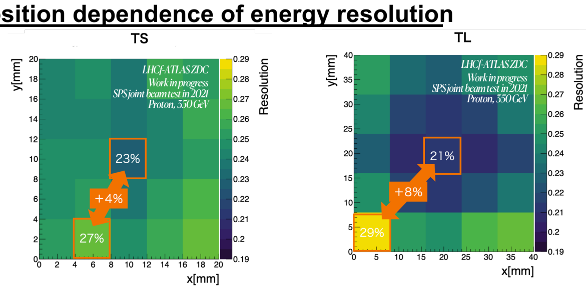
Position dependence of E_{rec}

The analysis region was divided into 5x5 areas to test the position dependence of energy reconstruction performance.



The z axis represents the ratio to E_{rec} mean in the center region. The mean of E_{rec} is uniform within ranges of -1% to +0.1% in TS and -4% to +1% in TL except the edge region. The ratio becomes smaller towards the edge.
A uniformity will be considered as a correction in the reconstruction analysis.

Position dependence of energy resolution



The energy resolution in the region except edge is 22.9-25.2% in TS, 20.9-22.1% in TL. The energy resolution is large in the edge region. This seems to be caused by the shower leakage.

6. Summary and future prospect

- We confirmed that energy resolution significantly improve to 21% by LHCf + ATLAS ZDC joint analysis from 40% by only LHCf analysis.
- It found that the reconstructed energy become quite uniform and energy resolution is good and uniform in the region except the edge of the detector.
- We are ready to analyze the data of operation carried out with LHCf + ATLAS ZDC in 2022. Accurate neutron analysis will make us to go next steps. For example, one-pion-exchange events can be selected with neutron energies in a large pseudo rapidity region.