

# Study of the long-range azimuthal correlations in $pp$ and $p+\text{Pb}$ collisions with the ATLAS detector at the LHC

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**Abstract.** ATLAS measurements of azimuthal correlations between particle pairs at large pseudorapidity separation in  $pp$  and  $p+\text{Pb}$  collisions are presented. The data were collected using a combination of the minimum-bias and high track-multiplicity triggers. The correlations in the “ridge” region are analysed using a new template fit method for extraction of flow harmonics. A comparison of this method with the previously used ZYAM method and a detailed study of the dependence of their results on the charged particle multiplicity and the transverse momentum of the particles forming a pair are shown.

## 1. Introduction

The measurements of Au+Au collisions and later of Pb+Pb collisions at very high energies revealed strong long-range azimuthal correlations between produced particles attributed to the creation of the Quark-Gluon Plasma (see [1] and references therein). The observation of similar in shape correlations (called “ridge”), though smaller in magnitude, in  $pp$  collisions at the LHC in events with very large multiplicities [2, 3] initiated more detailed studies [4] of  $pp$  and  $p+\text{Pb}$  collisions measured by the ATLAS detector [5], which are presented in this report.

The  $pp$  collisions measured at 2.76, 5.02 and 13 TeV and  $p+\text{Pb}$  collisions at 5.02 TeV are used in the analysis. As the most interesting phenomena are observed for events from the tail of the multiplicity distribution, the minimum bias sample of events was supplemented with events obtained using several High Multiplicity Triggers, which accept events with the number of reconstructed tracks above some threshold.

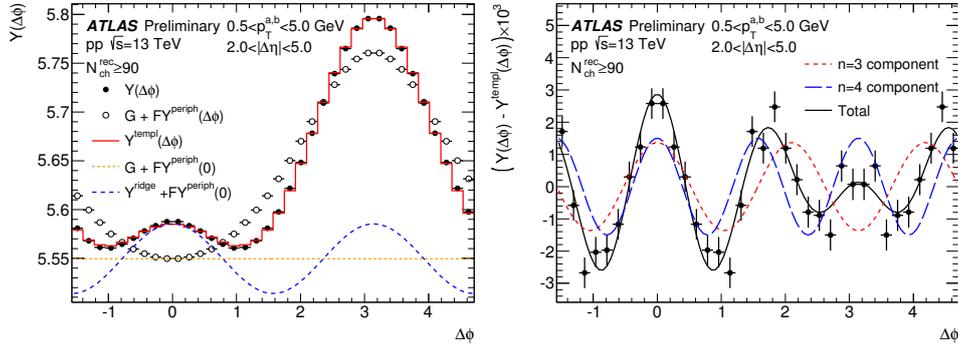
## 2. Template fit method

The two-particle correlation function,  $C(\Delta\eta, \Delta\phi)$ , is parameterized by the difference of pseudorapidities and the difference of azimuthal angles of two reconstructed tracks:

$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}, \quad (1)$$

where  $S(\Delta\eta, \Delta\phi)$  and  $B(\Delta\eta, \Delta\phi)$  denote the number of pairs in the measured events and that in mixed events, respectively. In the range  $|\Delta\eta| < 2$  this correlation function is dominated by short-range correlations from jets, resonance decays and Bose-Einstein effects. In order to study the long-range correlations this function is integrated over the remaining particle-pair acceptance





**Figure 1.** Left panel: Example of a template fit including only the 2nd order harmonic,  $v_{2,2}$ , to the per-trigger particle yields,  $Y(\Delta\phi)$ , in 13 TeV  $pp$  collisions [4]. Right panel: The difference between the  $Y(\Delta\phi)$  and the template fit, showing the presence of  $v_{3,3}$  and  $v_{4,4}$  components (note the large difference in the vertical scales).

of the ATLAS detector, i.e.  $2 < |\Delta\eta| < 5$ . The resulting one-dimensional function,  $Y(\Delta\phi)$ , is expected to contain contributions from hard processes (dijets),  $Y^{hard}(\Delta\phi)$ , and from the long-range correlation,  $Y^{ridge}(\Delta\phi) = G[1 + 2v_{2,2} \cos(2\Delta\phi)]$ . In previous analyses it was assumed that in the low-multiplicity events only effects of hard processes and a constant combinatoric contribution are present. In the ZYAM method (Zero Yield At Minimum) a constant pedestal was subtracted from the values of  $Y(\Delta\phi)$  for peripheral, low-multiplicity events and this function was then subtracted from results obtained at larger multiplicities.

There are however indications that the modulated “ridge” component is present even in events with the lowest multiplicities, thus a new template-based method was proposed [3, 4]. The yields  $Y(\Delta\phi)$  obtained for larger multiplicities are thus described by a template function:

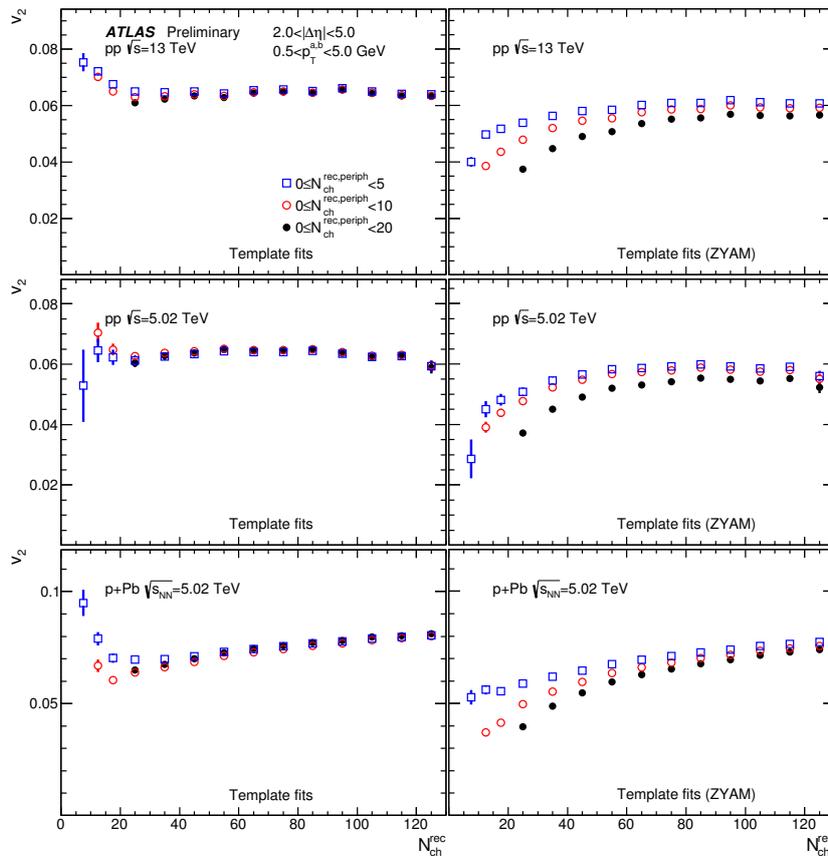
$$Y^{templ}(\Delta\phi) = FY^{periph}(\Delta\phi) + G[1 + 2v_{2,2} \cos(2\Delta\phi)] \quad (2)$$

where  $F$  and  $v_{2,2}$  are free parameters and  $G$  is fixed by normalization. The function with the second order harmonics very well approximates the data (Fig. 1 (left panel)), however in a closer examination of the difference between data points and the template, the contributions from higher harmonics are clearly visible (Fig. 1 (right panel)). These higher order terms were included in the template function and the values of  $v_n$  harmonics ( $n=2-4$ ) are obtained assuming  $v_n(p_{T_1}) = v_{n,n}(p_{T_1}, p_{T_2}) / \sqrt{v_{n,n}(p_{T_2}, p_{T_2})}$ , where  $p_{T_1}$  and  $p_{T_2}$  are transverse momentum intervals of the trigger and associated particle, respectively.

In Fig. 2 the  $v_2$  values obtained using the new template fit method and the ZYAM method are shown. For three different selections of the peripheral event sample, the template fit method gives consistent results, while the values of  $v_2$  from the ZYAM method are varying and are always smaller than those from the template fit. Such differences are expected in the presence of the  $\cos(2\Delta\phi)$  modulation in the peripheral events. In the ZYAM method such contribution is directly subtracted and thus the calculated  $v_{2,2}^{ZYAM}$  is reduced, while in the template fit method presence of this contribution leads to a change of the  $G$  parameter without significant modification of  $v_{2,2}^{templ}$ .

### 3. Results and conclusions

In Figure 3 all important properties of the long-range “ridge” correlations for  $pp$  and  $p+Pb$  collisions are summarized. For the two energies of  $pp$  collisions considered, 5.02 and 13 TeV, the

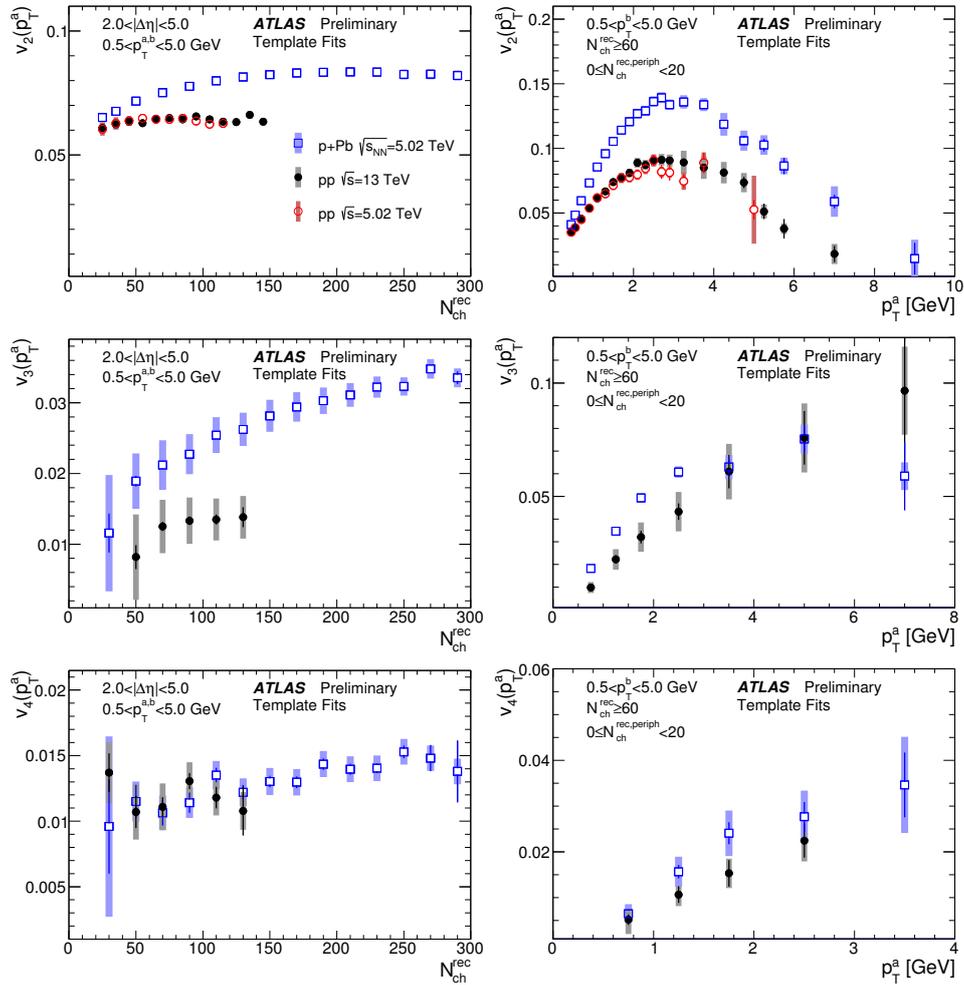


**Figure 2.** Dependence of  $v_2$  on the choice of the peripheral bin for the template fitting method (left panels) and ZYAM-based method (right panels) [4]. The top, middle and bottom panels correspond to 13 TeV  $pp$  collisions, 5.02 TeV  $pp$  collisions and 5.02 TeV  $p+Pb$  collisions, respectively.

$v_2$  values from the template method are very similar, both when presented as a function of event multiplicity and as a function of  $p_T$  of the trigger particle. In  $pp$  collisions there is no apparent dependence of  $v_2$ ,  $v_3$  or  $v_4$  on event multiplicity (the last two shown for 13 TeV only). This is in contrast with the results obtained for  $p+Pb$  collisions at 5.02 TeV, where all harmonics are growing with increasing multiplicity. The values of  $v_2$  and  $v_3$  are similar for  $pp$  and  $p+Pb$  collisions only for the lowest multiplicities, while in the case of  $v_4$  they seem to be similar in a wider multiplicity range.

The dependence of  $v_2$  on  $p_T$  of the trigger particle for high multiplicity events both for  $p+Pb$  and  $pp$  collisions (Fig. 3 right panels) has a shape similar to that observed earlier in collisions of nuclei. However, the maximal value of  $v_2(p_T)$  is about 1.5 times higher for  $p+Pb$  collisions than for  $pp$  collisions. The higher harmonics,  $v_3$  and  $v_4$ , are increasing with  $p_T$  for both systems at least up to 4 GeV. Their values are higher for  $p+Pb$  collisions, but the difference is relatively smaller than for  $v_2$ . Other results of the template fit method are shown in [3, 4].

In summary, the new template fit method applied to the  $pp$  and  $p+Pb$  data allows to calculate the values of flow harmonics,  $v_n$ . They do not depend on the selection of peripheral events and are always slightly higher than those obtained from the ZYAM method. In  $pp$  collisions  $v_n$  values do not depend on event multiplicity, in  $p+Pb$  collisions they are growing with increasing event



**Figure 3.** Comparison of the  $v_n$  obtained from the template fitting procedure in the 13 TeV  $pp$ , 5.02 TeV  $pp$ , and 5.02 TeV  $p+Pb$  data, as a function of multiplicity of reconstructed tracks,  $N_{ch}^{rec}$ , (left panels) and as a function of the transverse momentum,  $p_T$  (right panels) [4]. From top to bottom the rows correspond to  $n = 2, 3$  and  $4$  respectively. The error bars and shaded bands indicate statistical and systematic uncertainties, respectively.

multiplicity and are always larger than in  $pp$  collisions.

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