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Electroweak Physics in the Forward Region

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The lack of direct measurements of the so-called New Physics observables moves the attention of the high energy physics community towards the precise determination of the parameters that describe the electroweak sector of the Standard Model. The LHCb experiment at the LHC collider at CERN can exploit the favorable phase space coverage to reach the needed precision for these investigations. The recent results on the $Z^0 \to \mu^+\mu^-$ angular coefficients determination are summarised and discussed in this contribution.

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1. Introduction

The global analysis of the electroweak data [1] shows that the current measurements in this Standard Model (SM) sector are consistent with the predictions within the experimental and theoretical errors. The recent measurement of the W boson mass by the CDF experiment [2] has brought on the table the question if the precision achieved so far on the electroweak observables is sufficient to identify possible deviations that may be due to New Physics contribution. The longstanding discrepancies in the backward-forward asymmetry measured in different final states of the Z^0 boson decay and in the Weimberg angle were considered not an urgent issue to solve in the past. Now the new W mass measurement and new Top quark mass (see [1] for the discussion on m_{top}) determination together with the old tensions rise the suspect that some New Physics aspect may hide in the electroweak sector.

The LHCb detector [3] is a single-arm forward spectrometer instrumented in the pseudorapidity region $2 < \eta < 5$. It has been optimised for the study of $b-$ and $c-$hadrons by providing a robust tracking system and an excellent particle identification system. Its unique kinematic coverage allows it to perform measurements that are sensitive to both low and high values of Bjorken x and hence making LHCb complementary to ATLAS and CMS. The LHCb results on the W boson mass determination and other electroweak relevant measurements have been presented while here the focus is on the $Z^0 \to \mu^+\mu^-$ angular coefficients measurement.

2. Z^0 boson cross-section measurement

LHCb has reconstructed a sample of $Z^0 \to \mu^+\mu^-$ in 5.1 ± 0.1 fb^{-1} of data collected in the 2016-2018 data taking. The $\mu^+\mu^-$ candidates are required to have a pair of well-reconstructed muons with transverse momentum $p_T > 20$ GeV/c and pseudorapidity in the range $2 - 4.5$. These requirements allow to have an high signal to noise ratio as demonstrated by the left side plot on figure 1 [4] where the $\mu^+\mu^-$ invariant mass is shown. This sample of events is used to measure the production cross-section. The complete analysis and all the results are presented in [4]. Figure 1 on the right reports the differential cross-section as function of y^Z, the Z^0 boson rapidity. The measurement is compared with different theoretical predictions showing a very good agreement. The LHCb result represents the most precise Z^0 boson cross-section determination in the forward region and allows to test quantum chromo-dynamic (QCD) prediction and to constrain the proton parton distribution function.

3. Angular coefficient determination

The Drell-Yan $\mu^+\mu^-$ production near the Z^0 pole, but not only there, is an important source of information about electroweak parameters. LHCb has published the first measurement of the angular coefficient in the forward region [5] by using the 2016-2018 data collected at the center of mass energy of 13 TeV and the highlights are presented here.

The process $pp \to \gamma^*/Z + X \to l^+l^- + X$ where X represents any other particles can be described using eight frame-dependent angular coefficients, A_i $(i = 0, ..., 7)$. These coefficients depend on the invariant mass, p_T and rapidity y^Z of the lepton pair and are all zero at the leading-order approximation in the QCD framework except A_4 that is related to the parity violation in

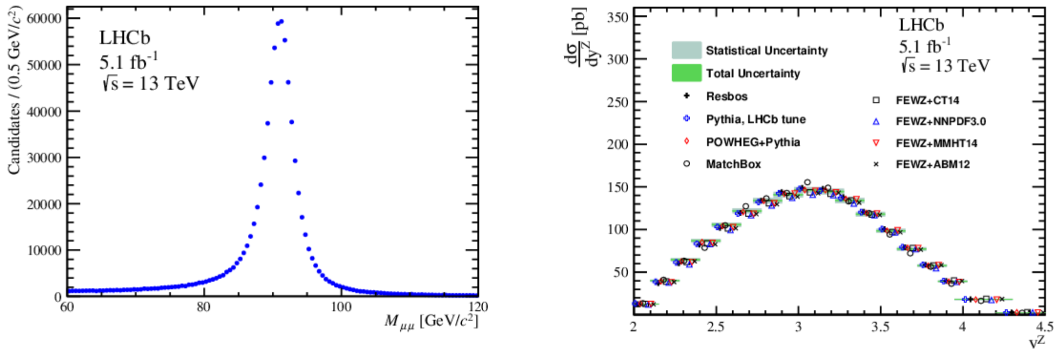

Figure 1: Left: Invariant mass distribution of the $\mu^+\mu^-$ pairs. Right: differential cross-section as function of the rapidity, y^Z, compared with different theoretical predictions.

the weak interactions. At the next-to-leading-order, A_{0-3} are different from zero, while A_{5-7} are expected to deviate from zero only at next-to-next-to-leading-order. The events are selected requiring an initial di-muons invariant mass $50 < M_{\mu\mu} < 120$ GeV/c^2 and $2 < y^Z < 5$. The parameters A_0, A_1, A_2 and A_3 are determined as function of p_T, shown in figure 2, and y^Z in the region $75 < M_{\mu\mu} < 105$ GeV/c^2. Due to the relative small data sample size the coefficients A_{5-7} are set to zero. The results, whose precision is limited by the are statistically error, demonstrate that:

- A_0 measurement is in good agreement with the predictions obtained by several Monte Carlo simulations, except PYTHIA8 in the high p_T region.
- A_1 experimental determination disagrees with PYTHIA8 in all p_T regions but is in agreement with all the other predictions.
- A_2 measurement is in agreement with all the predictions within the uncertainties. Additional investigation on A_2 will be discussed below.
- A_3 predictions underestimate the experimental results in the low momentum region.
- A_4 is commented below.
- The Lam-Tung relation $A_0 = A_2$, plotted in figure 2 as $A_0 - A_2$ is violated at high p_T consistently with what found by ATLAS [6] and CMS [7]. At low momentum the predictions are higher than the measurement while at high momentum the trend is opposite. In any case, more data are needed to have a conclusive statement.

The measurement of A_4 deserves a dedicated comment. The forward-backward asymmetry, defined as $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$ where $\sigma_{F(B)}$ is the integrated cross-section for $\cos\theta > 0 (< 0)$ (θ is the polar angle of the negative muon in the Collin-Soper frame) is proportional to A_4. LHCb has measured the asymmetry using data collected at center-of-mass energy of 7 and 8 TeV [8] and the determination with the $\sqrt{S} = 13$ TeV data set is in progress. This is the reason why figure 2 shows only ΔA_4, the error on A_4 and not its measurement. The error on A_4 is consistent with the predictions. This

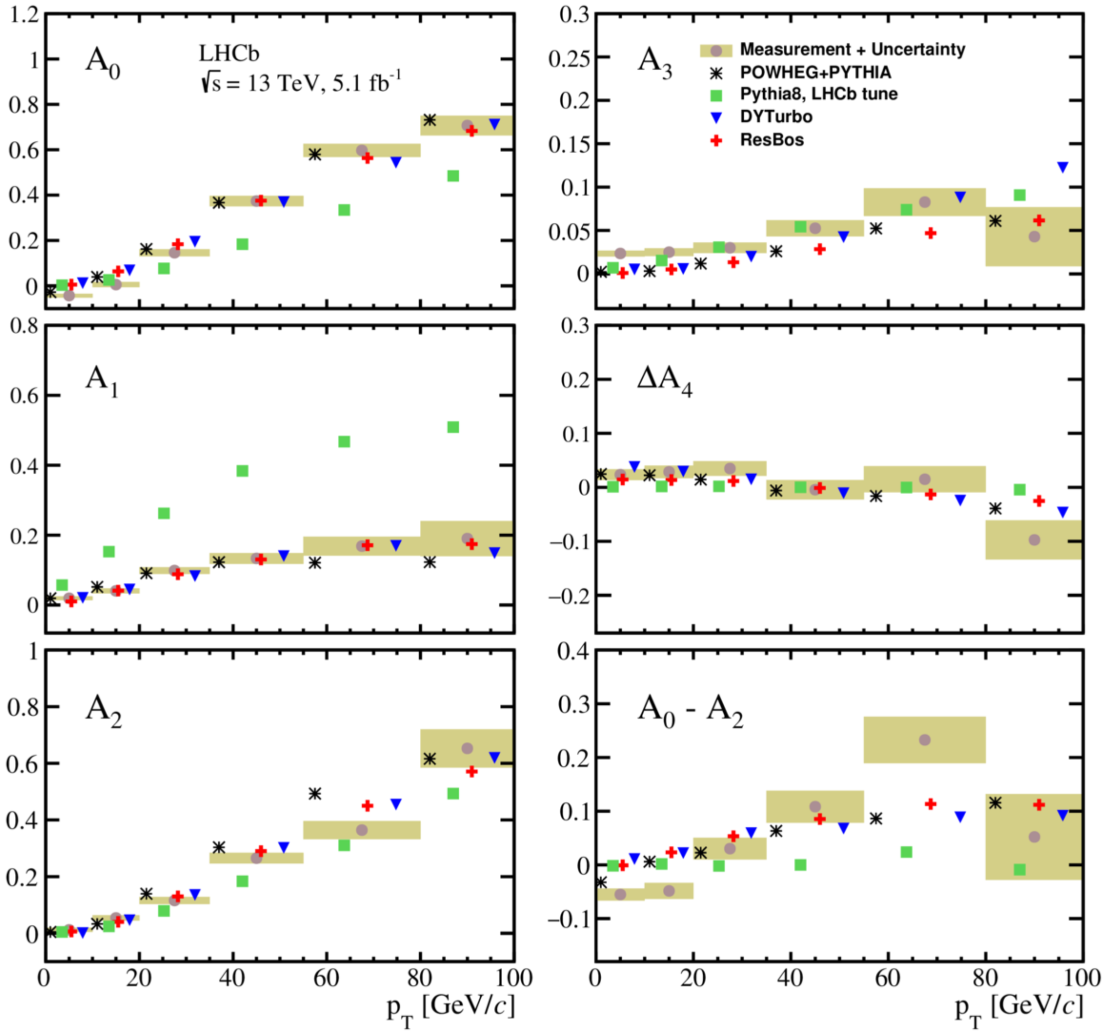

Figure 2: Comparison of the measured angular coefficients with different predictions, as a function of the Z-boson p_T, in the rapidity region of Z^0-boson $y^Z > 2$ and $75 < M_{\mu\mu} < 105$ GeV/c^2.

demonstrates that in the future LHCb can play an important role in solving the tensions on the Weimber angle having the possibility to provide one of the most precise measurement [9].

The coefficient A_2 is proportional to the convolution of two Boer-Mulders functions [10], of the quark and the antiquark. A Boer-Mulders function involves non-perturbative correlation between quark (antiquark) transverse momentum and transverse spin in an unpolarized nucleon. The A_2 measurement in the low p_T region probes the non-perturbative Boer-Mulders transverse momentum dependent nucleon parton distribution functions. Figure 3 shows A_2 as function of the dimuon p_T in three $M_{\mu\mu}$ intervals.

All the measurements are affected by the low statistics in fact the statistical error is the dominant uncertainty. Nevertheless, it can be noticed that data and predictions are in a reasonable agreement except in the low dimuon invariant mass region at low momentum (top left). Here the measurement

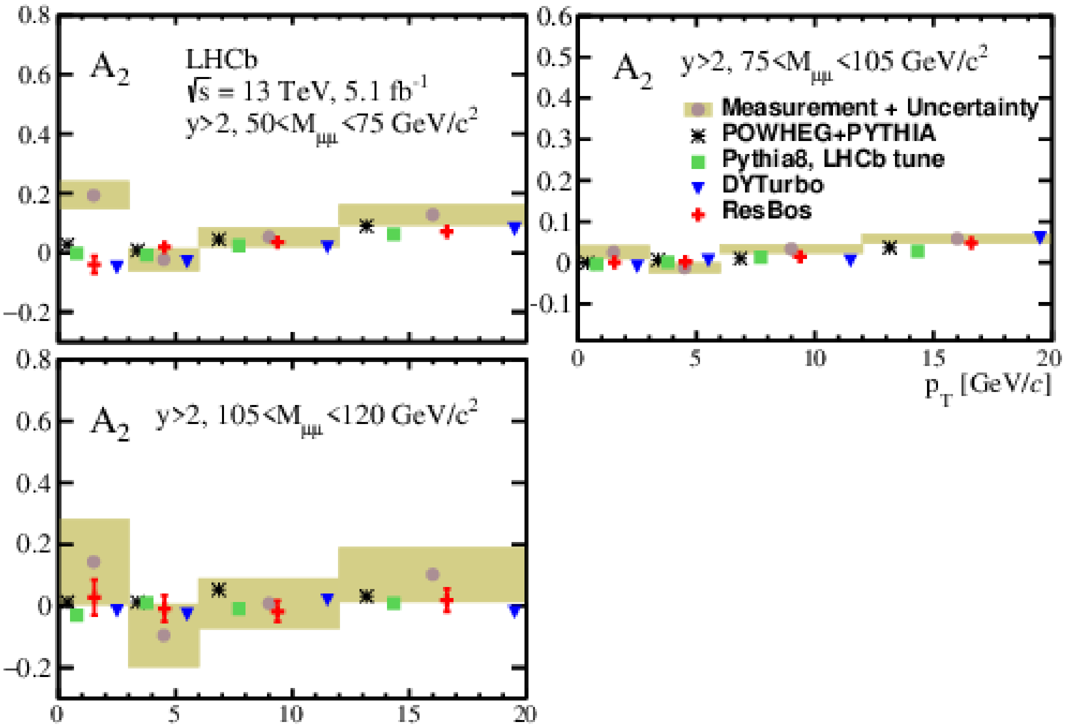

Figure 3: Comparison of the measured A_2 coefficient with different Monte Carlo predictions, as a function of the dimuons p_T for three different dimuons invariant mass regions.

is significantly higher of any prediction, but it is not possible to ascribe that to non-perturbative spin-momentum correlations in the proton since none of the predictions include them.

4. Conclusions

The LHCb experiment with its excellent performance in the forward region allows to test the electroweak sector of the SM in a phase space parameter which is complementary to ATLAS and CMS. The dimuon production measurements presented here are only the first step of LHCb in this area which makes the perspective for the future very interesting.

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