PROCEEDINGS OF SCIENCE

Measurement of the $\mathrm{t\bar{t}}$ cross-section and $\mathrm{t\bar{t}}$/Z cross-section ratio in pp collisions at $\sqrt{s} = 13.6\,\mathrm{TeV}$ with the ATLAS and CMS experiments

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Recent measurements of the inclusive $\mathrm{t\bar{t}}$ production cross section, $\sigma_{\mathrm{t\bar{t}}}$, and the ratio of $\mathrm{t\bar{t}}$ to Z boson production, $R_{\mathrm{t\bar{t}/Z}}$, are presented by the CMS and ATLAS collaborations using data collected from proton-proton collisions at the new LHC operating energy of $\sqrt{s} = 13.6\,\mathrm{TeV}$. These are among the first results of the ongoing LHC Run 3 data-taking period, which began in 2022, and provide a first opportunity to measure changes in key physics observables following the increase in energy. Both experiments used new techniques relative to previous measurements to obtain precise results efficiently, the methods of which are outlined and compared.

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1. Introduction

On July 5th 2022, the LHC at CERN achieved stable beams of colliding protons with a new record center of mass energy of $\sqrt{s} = 13.6\,\mathrm{TeV}$. This marked the beginning of the LHC's Run 3, a 4-year period of scheduled data-taking for the LHC experiments. Scientists at the CMS [1] and ATLAS [2] experiments were eager to extract physics measurements from this data as soon as possible. Doing so not only provides our first glimpse of physics at a brand new energy frontier, but also serves as validation for the new data and affirms its physics potential.

Two processes which are easy to identify among the mountains of new data are top quark pair production ($t\bar{t}$) and Z-boson decays. Both can contain leptons with high transverse momentum (p_T), which are well-reconstructed if they are electrons or muons. The case of $t\bar{t}$ production is further distinguished from other processes by the presence of heavy-flavor b-quark jets, which can be tagged and distinguished from other light quark jets. On the other hand, Z-boson decays can be identified by their proximity to the Z-mass resonance, and are produced at higher rates than top quark pairs at the LHC.

As it is the heaviest standard model particle, top quark pair production has only become possible at modern high energy colliders. After first being observed and measured in proton-antiproton collisions produced by the Tevatron at $\sqrt{s} = 1.96\,\mathrm{TeV}$ [3], subsequent top quark pair production measurements have only been possible at the LHC. There, the $t\bar{t}$ cross section from proton-proton collisions has since been measured at 4 energies by CMS and ATLAS, as well at 3 energies in the forward regime by the LHCb experiment (see references in [4, 5]). The raising of the LHC beam energy in 2022 provides a crucial opportunity to verify the energy dependence of $\sigma_{t\bar{t}}$ at a 5th energy from LHC data.

In fact, the rate of $t\bar{t}$ production is particularly sensitive to the energy increase that came with LHC Run 3. While the increase in $\sqrt{s} = 13.6\,\mathrm{TeV}$ from the Run 2 value of 13 TeV marks a change of less than 5%, the inclusive cross section for top quark pair production, $\sigma_{t\bar{t}}$, is predicted to rise by about 10%, from 834 pb to 924 pb [6, 7]. This makes $\sigma_{t\bar{t}}$ a prime physics observable to test the effects of the LHC energy increase against our best models. Meanwhile, Z decays can be used by both CMS and ATLAS collaborations for separate measurements and to mitigate uncertainty on early luminosity estimates.

We will discuss two complementary approaches to studying these processes at the new energy frontier: the CMS measurement of $\sigma_{t\bar{t}}$ which yielded the first physics publication of LHC Run 3 [4], and the ATLAS measurement of $\sigma_{t\bar{t}}$ alongside the $t\bar{t}$ to Z boson production ratio which yielded the recent preprint [5].

2. CMS measurement

CMS developed an ambitious new strategy to perform a precise measurement using only 1 fb^{-1} of data and a combination of multiple $t\bar{t}$ decay channels [4]. While Z boson production is considered only as a background process in this measurement strategy, we note that this process has also been studied by the CMS collaboration using 2022 data, with Z+jets events used to verify early luminosity estimates [8] and to report a preliminary measurement of the inclusive Z boson production cross section [9].

For the determination of $\sigma_{\mathrm{t\bar{t}}}$, events were studied in both the lepton+jets channel as well as in the dilepton channel, targeting events in the eμ, ee, $\mu\mu$, e+jets, and μ+jets channels. All channels were used together to perform a maximum likelihood fit and extract the inclusive $\sigma_{\mathrm{t\bar{t}}}$. Data was collected over a short period in July-August 2022 with an average number of pp interactions per bunch crossing of around 40.

Events were selected with one or two leptons having a transverse momentum of $p_{\mathrm{T}} > 35\,\mathrm{GeV}$. This differs from other measurements, where different selection requirements are typically used for the different channels to maximize the event acceptance rate. By keeping the p_{T} selection uniform, if the p_{T} distribution is also identical across channels to good approximation, then the ID efficiency can be reduced to a scalar efficiency factor applied once per lepton. This allows an entirely in situ cross-check of the lepton ID efficiencies following the method used for the preliminary result [10]. The ability of the channel combination to constrain lepton ID efficiencies is also reflected in the final likelihood fit.

Jets are reconstructed with an algorithm that subtracts contributions from charged and neutral hadrons originating from pileup events [11]. Only jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ are considered. Events in the dilepton channels are required to have at least 1 jet, while events in the lepton+jets channels are required to have at least 3 jets. The DeepJet algorithm [12] is used to tag jets originating from b quarks. With the exception of the eμ channel, events are required to have at least 1 b-tagged jet.

Events are categorized by lepton flavor, the number of b-tagged jets, and overall jet multiplicity. All categories were found to not alter the lepton p_{T} distribution significantly, assuring the validity of the cross-check mentioned above. Lepton p_{T} distributions are shown in Fig. 1.

Lepton ID efficiencies are primarily determined via a “tag and probe” method [13] using a Z+jets-enriched sideband in the analyzed dataset, as this method has lower uncertainty than the *in situ* approach. However, in the likelihood fit, the channel combination provides complimentary information and the efficiency is further constrained.

The effect of b-tagging efficiency differing between data and simulation is modeled with an analytic formula. Like the lepton ID efficiencies, the uniform selection and b jet kinematics across channels allow the corresponding efficiency to be reduced to a scalar factor. This factor is then determined as part of the final likelihood fit, where it is allowed to vary freely.

The agreement of data and simulation after performing the likelihood fit is shown in Fig. 2. The likelihood fit yields a cross section value of

$$\sigma_{\mathrm{t\bar{t}}} = 881 \pm 23\,(\mathrm{stat{+}syst}) \pm 20\,(\mathrm{lum})\,\mathrm{pb}. \tag{1}$$

The luminosity, lepton ID efficiencies, and b-tagging efficiency were found to be the limiting uncertainties. Other notable sources of uncertainty had significantly less effect, although several were non-negligible, including the jet energy calibration, background cross sections, and pileup. The obtained value is in reasonable agreement with the standard model prediction of $\sigma_{\mathrm{t\bar{t}}}^{\mathrm{pred.}} = 924^{+32}_{-40}\,\mathrm{pb}$, which was calculated via TOP++ at NNLO+NNLL precision using the PDF4LHC21 parton distribution function (PDF) set [14]. Uncertainties on the theory prediction include variation of the matrix element scales, uncertainty on the PDF set following the PDF4LHC recommendations, and uncertainty on the value of α_{S} used by the PDF set. The result is shown alongside other CMS results at different energies in Section 4.

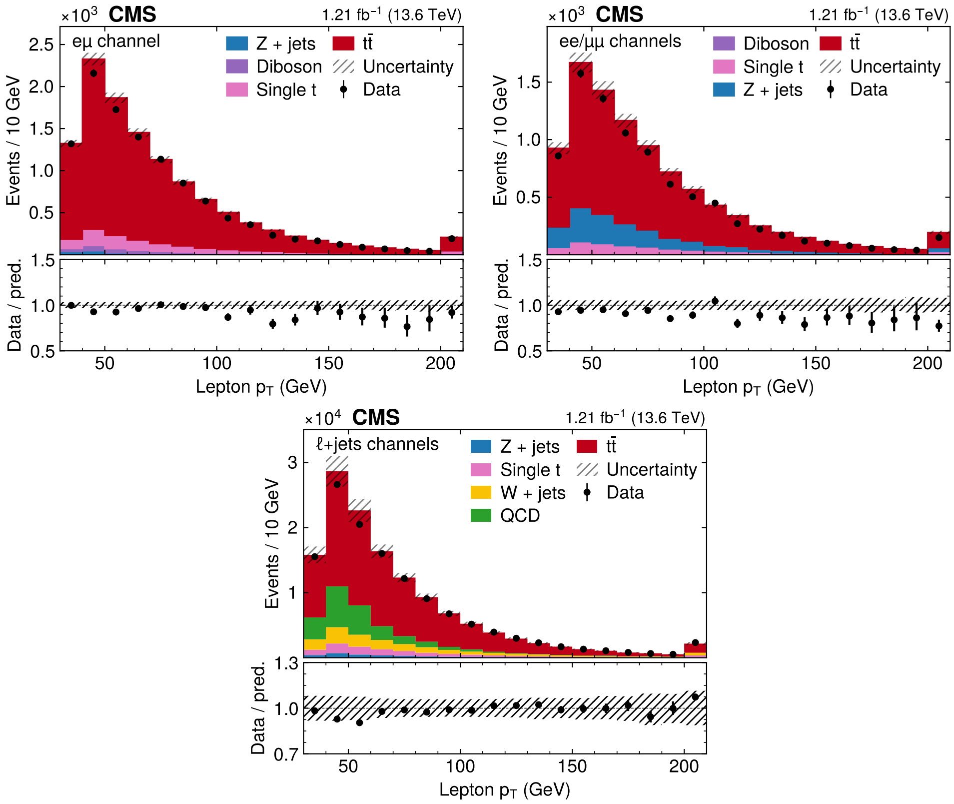

Figure 1: The agreement between data and simulation is shown for the distribution of reconstructed lepton p_{T}. This is shown separately for events in the eμ channel (top left), events in the ee/$\mu\mu$ channels (top right), and events in the lepton+jets channel (bottom) [4].

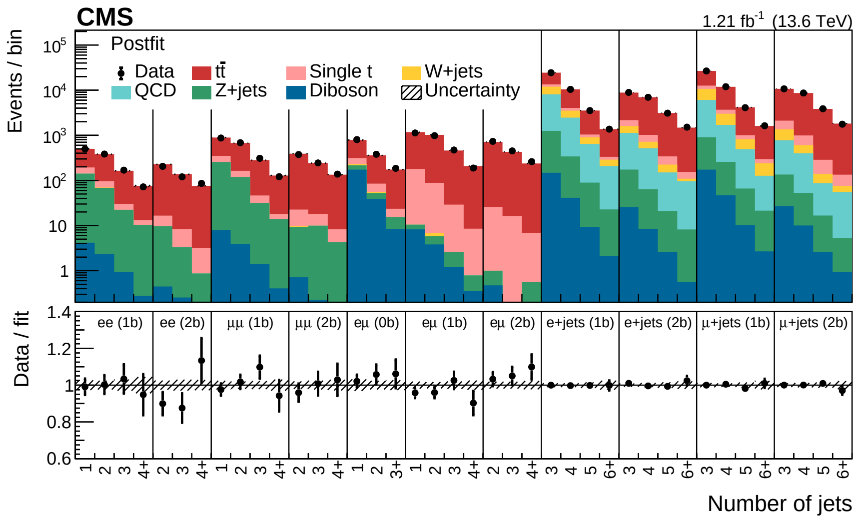

Figure 2: After performing the maximum likelihood fit, the resulting agreement between data and simulation is shown, along with the total postfit uncertainty excluding luminosity. We see that the fit is able to find good agreement between the model and the data [4].

As a cross-check on this new method performed with early data, a separate result is obtained using an event counting method in the eμ channel only. This method uses events with at least 2 jets and enforces no b-tagging requirement, relying on a lower-statistics region with high purity. This alternate eμ-only event counting method yields a result of $\sigma_{t\bar{t}}$ = 888 ± 34 (stat+syst) ± 20 (lum) pb, in good agreement with the channel combination likelihood fit.

3. ATLAS measurement

ATLAS uses a combination of different channels to report measurements of the top pair production cross section $\sigma_{t\bar{t}}$ as well as its ratio to the Z boson production ratio, $R_{t\bar{t}/Z} \equiv \sigma_{t\bar{t}}/\sigma_Z$ [5]. While the $t\bar{t}$ cross section was determined from the high-purity eμ channel, events with two same-flavor leptons (electrons or muons) were considered as part of a Z+jets-enriched region (see Fig. 3) in order to gain simultaneous sensitivity to σ_Z. The measurement is performed on 29 fb^{-1} of data collected during 2022.

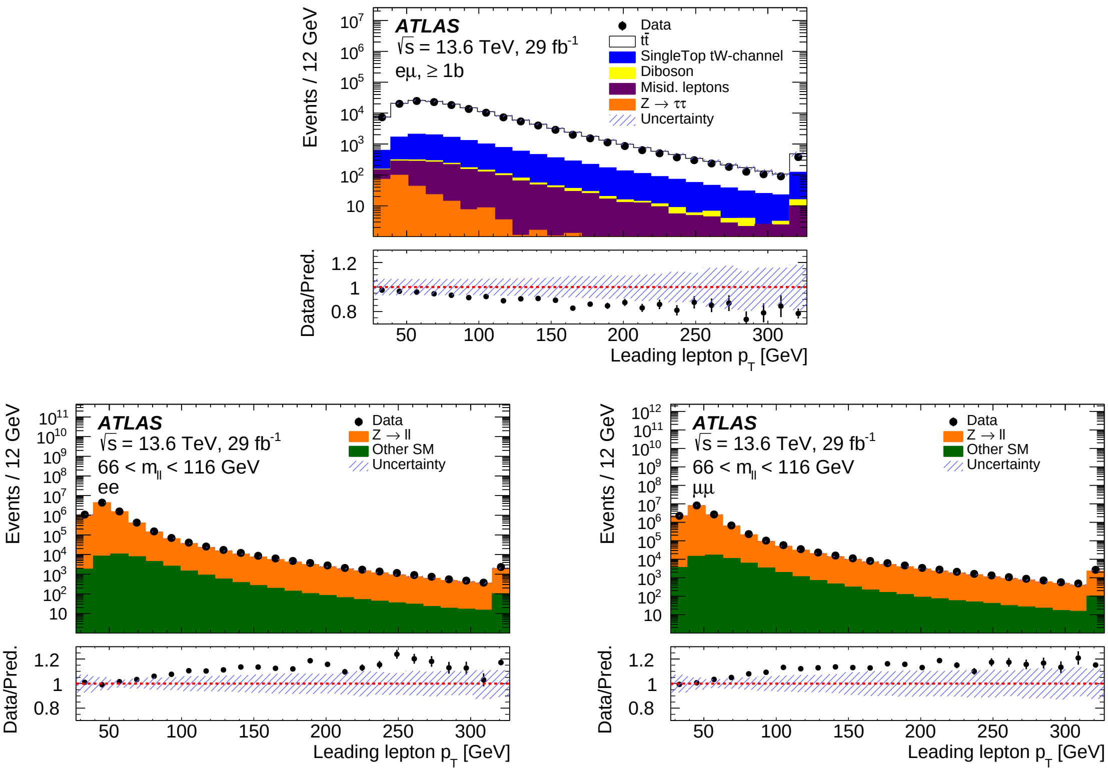

Figure 3: The agreement between data and simulation is shown for the distribution of reconstructed lepton p_T. This is shown separately for events in the eμ channel (top), events in the Z+jets-enriched ee channel (bottom right), and events in the Z+jets-enriched $\mu\mu$ channel (bottom right) [5].

Taking a ratio in this manner allows for significant gains in precision due to the cancellation of luminosity dependence. In particular, this can allow for a precise result even before the Van der Meer scans necessary for precision luminosity estimates at the LHC are performed and analyzed. Uncertainties on lepton ID efficiencies also benefit from significant cancellation in the ratio. The

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ratio $R_{\mathrm{t\bar{t}/Z}}$ allowed for a luminosity-independent measurement to achieve impressive precision as one of the earliest preliminary results of LHC Run 3 [15], while the measurement of $\sigma_{\mathrm{t\bar{t}}}$ benefited from updated determination of 2022 delivered luminosity to yield the result discussed in these proceedings [16].

This ratio is not only of practical interest, but also of physical interest due to its dependence on the quark/gluon parton distribution function (PDF) fraction. The dominant production mode for $\mathrm{t\bar{t}}$ pairs is gluon-gluon fusion, while Z bosons are primarily produced from $\mathrm{q\bar{q}}$ annihilation, making $R_{\mathrm{t\bar{t}/Z}}$ a useful quantity in testing the predictions of different PDF sets.

In the $\mathrm{t\bar{t}}$-enriched $\mathrm{e}\mu$ channel, events are considered with 1 or 2 b-tagged jets. Jets are identified as having originated from a b quark using the DL1d flavor tagging algorithm [17]. An overall b-tagging efficiency factor ϵ_{b} is then determined by the yields N_1 and N_2 in these two channels via the analytic yield formulas

$$N_1^{\mathrm{sig}} = L\sigma_{\mathrm{t\bar{t}}}\epsilon_{\mathrm{e}\mu}2\epsilon_{\mathrm{b}}(1 - C_{\mathrm{b}}\epsilon_{\mathrm{b}}) + N_1^{\mathrm{bkg}}, \quad (2)$$
$$N_2^{\mathrm{sig}} = L\sigma_{\mathrm{t\bar{t}}}\epsilon_{\mathrm{e}\mu}C_{\mathrm{b}}\epsilon_{\mathrm{b}}^2 + N_2^{\mathrm{bkg}}, \quad (3)$$

where $\epsilon_{\mathrm{e}\mu}$ is the efficiency for a $\mathrm{t\bar{t}}$ event to pass the opposite sign lepton selection criteria and C_{b} is a correlation constant which can deviate from unity if the probability of independently tagging each of two b jets is not independent in practice. This effect is estimated from simulation, and C_{b} is observed to have only a small deviation from unity.

The same- and different-flavor lepton channels are fit together to simultaneously extract $\sigma_{\mathrm{t\bar{t}}}$, $R_{\mathrm{t\bar{t}/Z}}$, and ϵ_{b}. The resulting agreement of data with simulation is shown in Fig. 4 (left), where we can observe very good compatibility. The extracted values for top pair production cross section and the ratio of $\mathrm{t\bar{t}}$ to Z production are

$$\sigma_{\mathrm{t\bar{t}}} = 850 \pm 3\,(\mathrm{stat.}) \pm 18\,(\mathrm{syst.}) \pm 20\,(\mathrm{lumi.})\,\mathrm{pb}, \quad (4)$$
$$R_{\mathrm{t\bar{t}/Z}} = 1.238 \pm 0.003\,(\mathrm{stat.}) \pm 0.21\,(\mathrm{syst.}) \pm 0.002\,(\mathrm{lumi.}), \quad (5)$$

compared to the predicted values of $\sigma_{\mathrm{t\bar{t}}}^{\mathrm{pred.}} = 924^{+32}_{-40}$ pb and $R_{\mathrm{t\bar{t}/Z}^{\mathrm{pred.}}} = 1.238^{+0.063}_{-0.071}$, both evaluated using the PDF4LHC21 [14] PDF set and a top quark mass of 172.5 GeV. Comparisons to different predictions of $R_{\mathrm{t\bar{t}/Z}}$ resulting from different choices of PDF set and top quark mass are shown in Fig. 4 (right), while the $\sigma_{\mathrm{t\bar{t}}}$ result is shown alongside other ATLAS results in Section 4.

Additionally, a separate fit is performed using only the same-flavor channels to obtain the fiducial Z-boson production cross section value of $\sigma^{\mathrm{fid.}}_{\mathrm{Z}\to\ell\ell} = 744 \pm 11\,(\mathrm{stat.{+}syst.}) \pm 16\,(\mathrm{lumi.})\,\mathrm{pb}$, in good agreement with the predicted value of $\sigma^{\mathrm{fid.}}_{\mathrm{Z}\to\ell\ell} = 746^{+21}_{-22}$ pb.

4. Summary

The CMS and ATLAS collaborations present some of the first results of LHC Run 3, using data collected from proton-proton collisions at the new record center of mass energy $\sqrt{s} = 13.6\,\mathrm{TeV}$. CMS and ATLAS both report measurements of $\sigma_{\mathrm{t\bar{t}}}$, representing the fifth energy at which the quantity has been measured by each experiment and the 6th in the history of particle physics experiment. The resulting values are in good agreement with one another, lying slightly below the prediction a the level of 1.1 standard deviations (CMS) and 1.5 standard deviations (ATLAS). Both

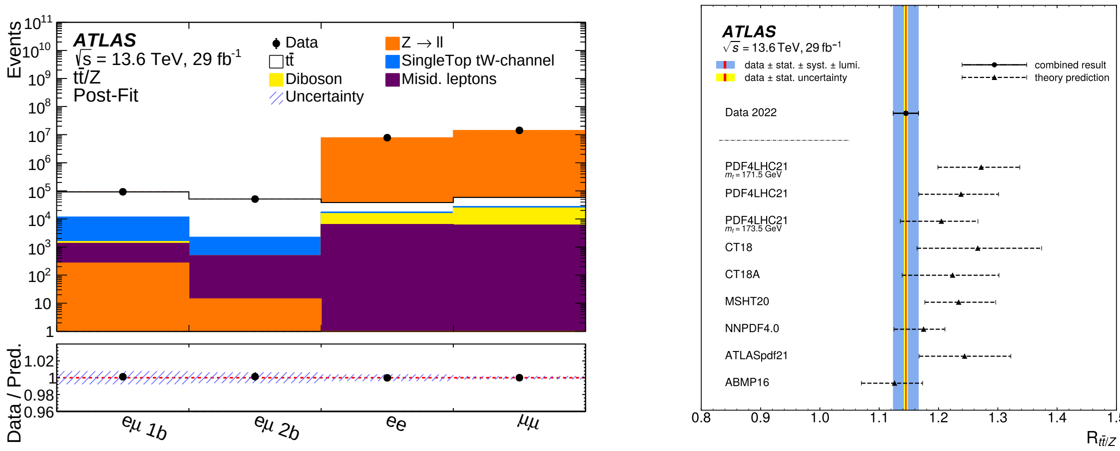

Figure 4: The agreement of data and simulation in the four separate event categories used by the fit is shown (left). The result for $R_{\mathrm{t\bar{t}}/Z}$ is shown and compared with predictions from different PDF sets, as well as different values of the top quark mass, which assumes a value of 172.5 GeV unless otherwise noted (right) [5].

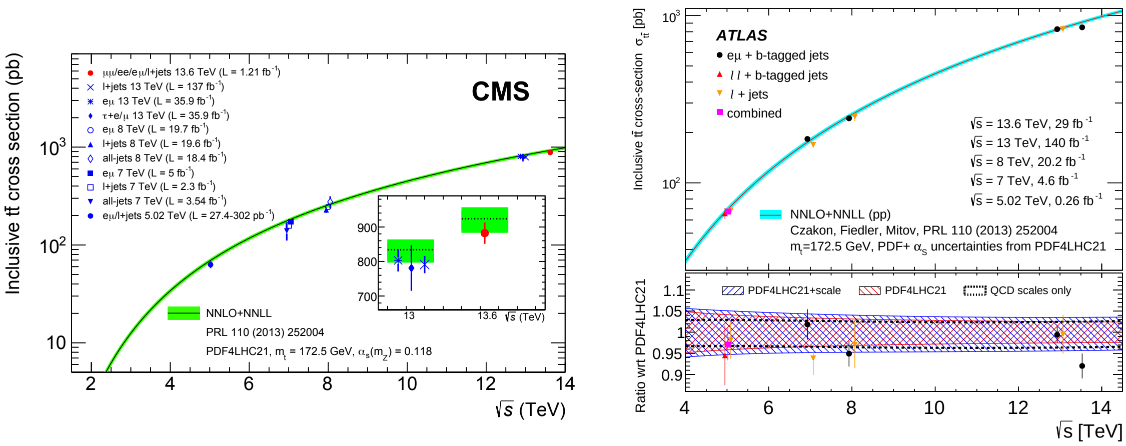

Figure 5: Summary plots showing the agreement of $\sigma_{\mathrm{t\bar{t}}}$ measurement with theoretical predictions at different values of $\sqrt{s}$ are shown for the CMS (left) [4] and ATLAS (right) experiments [5].

results are shown in comparison with the predicted energy dependence of $\sigma_{\mathrm{t\bar{t}}}$, along with other measurements performed at different values of $\sqrt{s} = 13.6\,\mathrm{TeV}$, in Fig. 5.

Both collaborations use intricate channel combinations of lepton flavors to accomplish their measurements. CMS uses a channel combination to constrain uncertainty sources in situ, while maximizing the potential of 1 fb^{-1} of data collected 2022. ATLAS uses a different channel selection to simultaneously extract the ratio of $\mathrm{t\bar{t}}$ to Z boson production, $R_{\mathrm{t\bar{t}}/Z}$. Both experiments use novel techniques to demonstrate the early physics potential of new data that is being collected during LHC Run 3, testing our understanding of particle physics at a new energy frontier.

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