PROCEEDINGS OF SCIENCE

Recent results in Standard Model Physics

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This report presents a compilation of selected recent Standard Model measurements, including findings by ATLAS, CMS, LHCb, and H1. Covered topics include QCD studies using jets, photons, and vector bosons, and the latest measurements of the strong coupling constant. Additionally, it includes a status update on the precision measurements of the W-boson and top-quark masses. It presents recent findings on inclusive multiboson production, studies in vector boson scattering, and selected top-quark physics results. These measurements and studies are crucial for rigorous testing of the Standard Model, and any deviations from the Standard Model predictions could indicate the presence of New Physics phenomena.

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1. Introduction

The Standard Model (SM) of particle physics precisely predicts production cross sections over an impressive span of 15 orders of magnitude, all the way from recent total cross-section measurements [1] to the most rare processes under study today. Recent achievements include the observation of processes such as four-top-quark production [2, 3], single-top-quark production in association with a photon $t\gamma$[4], WWγ[5], WZγ [6], W$\gamma\gamma$ production [7], and evidence of tWZ production [8]. These processes, today considered rare, may well evolve into domains of precision physics, similar to the progression from the Higgs discovery to the current extensive Higgs measurement precision program: Today's rare processes are tomorrow's precision physics.

The study of the SM involves two main objectives: finding deviations that could suggest new physics, accessing energy scales which may be beyond the reach of present colliders, and leveraging its processes for direct searches for BSM. Both objectives are supported significantly by continuously improved experimental methods, e.g. in luminosity determination, energy scales, and object identification.

In these proceedings, a selection of recent results in Standard Model Physics is presented, as available at the time of the EPS-HEP 2023. These include results by ATLAS, CMS, LHCb, and H1. Tests of QCD using Jets and Photons are presented in section 2, recent results on vector boson physics are summarized in section 3, W and top mass measurements in section 4, a brief summary of the status of top quark studies is given in section 5, diboson, triboson, and more rare processes are discussed in section 6, and section 7 concludes the proceedings.

2. Tests of QCD including α_S, Photons, Jets, and Jet Substructure

Recent measurements involving jets and photons have provided new insights into QCD. These include differential production cross-section measurements and, e.g., the study of their impact on parton distribution functions, but also new jet substructure measurements and a wide variety of new results constraining the strong coupling constant α_s using different approaches.

A new measurement of inclusive isolated-photon cross section by ATLAS on full Run 2 data [9] is performed for different isolation requirements to remove photons from the jets, determining cross-sections at different pseudorapidities and comparing to NLO and NNLO predictions. Figure 1 shows Theory/Data ratios and the spread of different PDF sets confronted with the new measurement. The new input is an important test of pQCD and provides constraints on gluon PDFs in particular.

For the inclusive jets measurement of CMS with 2016 13 TeV Data [10], jets are reconstructed using the anti-kT algorithm using an R parameter of 0.7 or 0.4 and unfolded to the particle level. In a recent addendum to the main part of the publication, there is a full QCD fit at NNLO, which leads to an improved precision of the gluon pdf with respect to DIS-only data as shown in Figure 1. PDFs and α_S are determined simultaneously and the extracted $\alpha_s(m_Z) = 0.1166 \pm 0.0017$ (1.5% rel.) is currently the most precise α_S from jet measurements and begins a series of recent α_S measurements reported at the conference.

One new measurement released by CMS at the time of the conference [13] exploits azimuthal correlations and defines a version of $R_{\Delta\phi}(p_T)$ which relates topologies with at least three jets with the inclusive jets case. A 2D unfolding is done and the observable is very sensitive to α_S. The

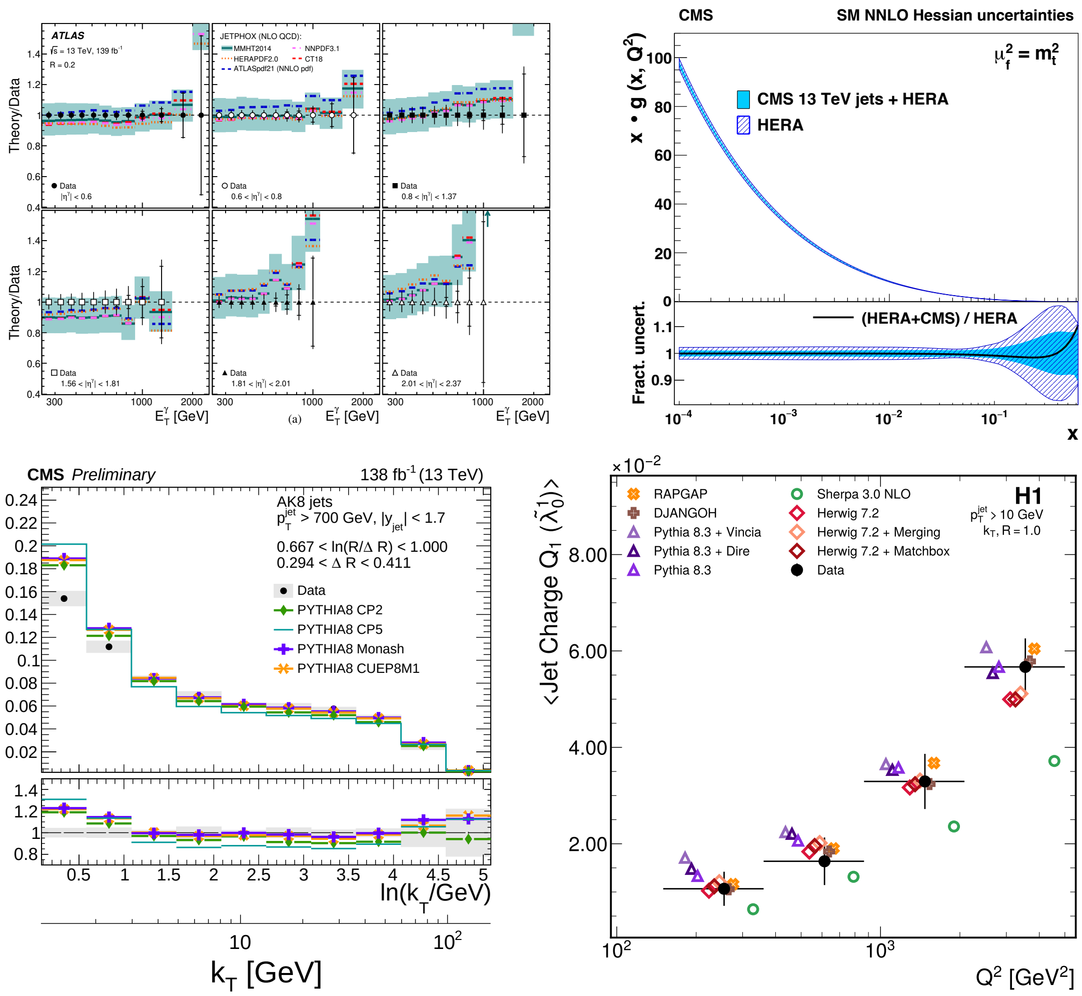

Figure 1: Upper left: Theory/data ratios of the inclusive photon production cross-sections at different pseudorapidities and for different PDF sets at NLOW [9]; Upper right: Gluon PDF constraints by adding 13 TeV inclusive jet cross section to PDF fit [10]; Lower left: Slice of Lund Jet Plane by CMS [11]; Lower right: Multidifferential jet substructure measurement in high Q^2 DIS events [12].

determination is performed in ranges of p_T enabling the study of the running of the coupling, with a value at the Z mass scale of $\alpha_s(m_Z) = 0.117^{+0.0117}_{-0.0074}$ (< 10% rel.). The limiting factor for the precision is the scale uncertainty and there is also a spread of results depending on the PDF choice.

A full Run 2 measurement by ATLAS to estimate the running of α_S in multijet events [14] proceeds by measuring event shape observables. These energy-energy correlations have a large sensitivity to QCD radiation and α_S. The measurement adds towards the high end of the kinematic range and gives a competitive value of α_S at the Z mass scale, $\alpha_s(m_Z) = 0.1175^{+0.0035}_{-0.0018}$ (< 3% rel.).

Two-point energy correlators E2C and 3-point energy correlators E3C inside jets were used for α_S determination in a novel CMS measurement [15]. The premise of the measurement is that the ratio of E3C and E2C is a linear function of α_S. Determining the slope is a powerful handle on the strong coupling, which mitigates the usual difficulties in extracting α_S from jet substructure, namely the degeneracy between q/g fraction and strong coupling in the observables. The intermediate result

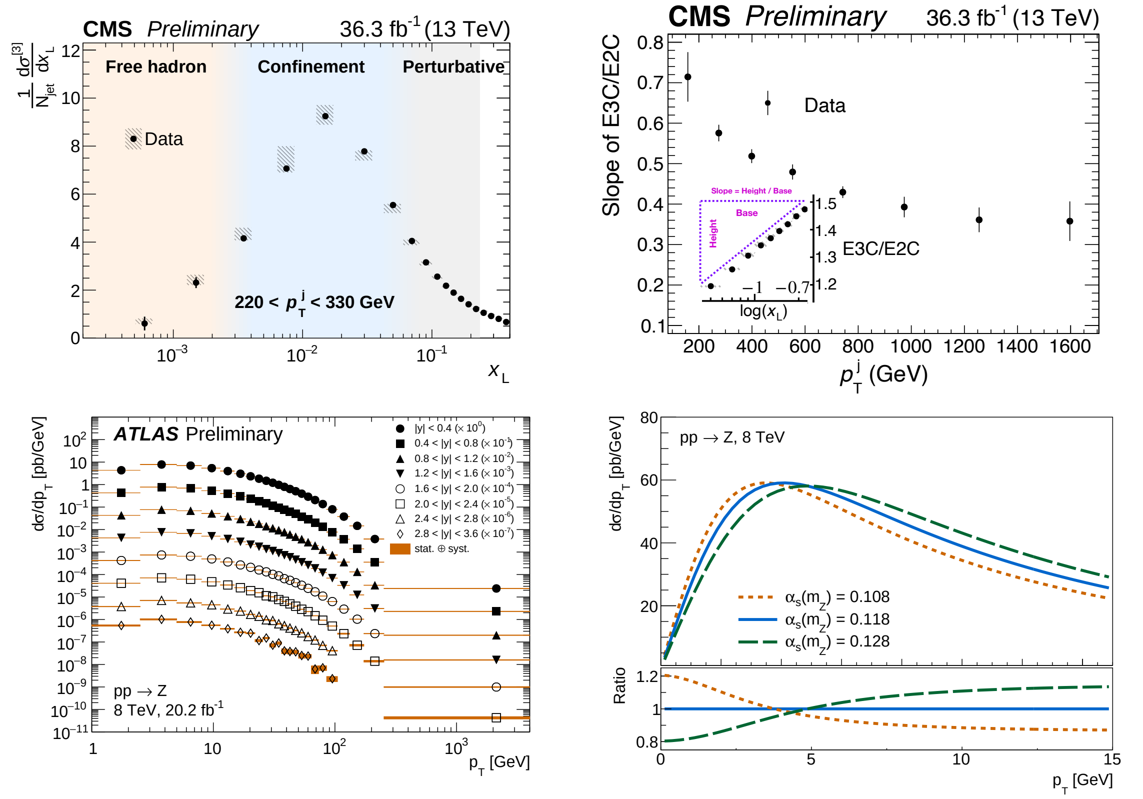

Figure 2: Upper left: 3-point energy correlators E3C inside jets by CMS [15]; Upper right: E3C/E2C ratio used for α_S determination [15]; Lower left: Measurement of Z p_T spectrum [16]; Lower right: Sensitivity of Z p_T spectrum to α_S used for α_S determination [14]

of unfolded E3C touches directly upon different regimes of QCD, ranging from parton interaction via the phase transition from parton to hadron to non-interacting hadrons. The E3C distribution and slope determination are shown in Figure 2 and the currently most precise α_S from jet substructure is $\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$ (< 4.1% rel.).

A preliminary result [14] based on 8 TeV data and the precise Z boson momentum distribution measurement is the most precise experimental determination of α_S to date. The rational for the measurement is that Z bosons recoil against QCD ISR, leading to the position of the Z-p_T peak being highly sensitive to α_S as illustrated in Figure 2. In comparison to other α_S determinations, the uncertainty of this single measurement is on par with the world average and the lattice QCD determination with an overall $\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}$ (0.7%rel.).

There is a growing array of measurements to look beyond single observables for jet substructure studies, which give a handle on many aspects of QCD. Following the theory proposal [17] of measuring the Lund jet plane, all LHC experiments are actively pursuing it. A recent addition is the CMS measurement on full Run 2 data [11]. The comparison to theory predictions and e.g. detailed study of Lund plane slices as shown in Figure 1 can be used as input to improve event generators and for future developments of parton showers with corrections beyond leading-log accuracy. The study of jet substructure is also pursued in legacy datasets: For example, H1 data from 2006 and 2007 is analysed using a novel ML-based unfolding technique for a multi-differential jet substructure

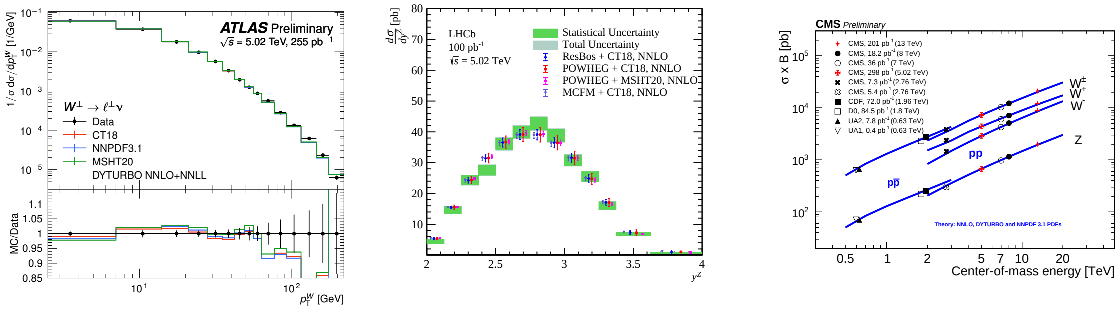

Figure 3: Left: Forward Z-boson cross-section measurement at 5.02 TeV [18] Centre: Low PU W p_T spectrum and comparison to theory predictions [19] Right: Cross-section of $W^+/W^-/W/Z$ at different centre-of-mass energies [20].

measurement in high Q^2 DIS events [12]. As illustrated in Figure 1, the achieved precision enables new insights to distinguish between different state-of-the-art predictions.

3. Vector Boson Physics

The Drell-Yan process is an important standard candle and a number of W/Z precision and differential measurements were discussed during the conference. In particular differential measurements provide an important insight on different QCD aspects and by constraining these one can work to achieve low modelling uncertainties in measurements of electroweak parameters.

The recent measurement at 8 TeV of Z-boson production properties in the full phase space of the decay leptons [16] is crucial input to the α_S determination mentioned in Section 2. It extrapolates from the fiducial volume to full phase space and is presented as a function of the Z p_T for different rapidity ranges, see Figure 2. Comparisons to N3LO QCD predictions and N4LL resummation show good agreement.

Measurements of forward Z-bosons with LHCb take advantage of the unique coverage of LHCb to enable complementary measurements to ATLAS/CMS. [21] is the most precise measurement in the forward region at 13 TeV and a new result at 5 TeV was submitted at the time of the conference [18]. The rapidity dependence at 5 TeV is shown in Figure 3.

Similarly to [16], there have been recent measurements of W and Z cross sections and p_T spectra at 5 and 13 TeV in low PU conditions to avoid the recoil contamination [19]. In particular the low p_T measurements and predictions are an important ingredient for future measurements of the W-boson mass and DYTURBO gives a good agreement as shown in Figure 3.

The total inclusive and fiducial W and Z boson production cross sections at 5.02 and 13 TeV have also been measured by CMS, separately for $W^+/W^-/W/Z$. The analysis [20] compares the individual channels to theory predictions, as well as relevant ratios between the channels and at different centre-of-mass energies. An evolution of the inclusive cross-section values from previous colliders to LHC is shown in Figure 3. A similar preliminary result has been released in the Z channel at 13.6 TeV [22].

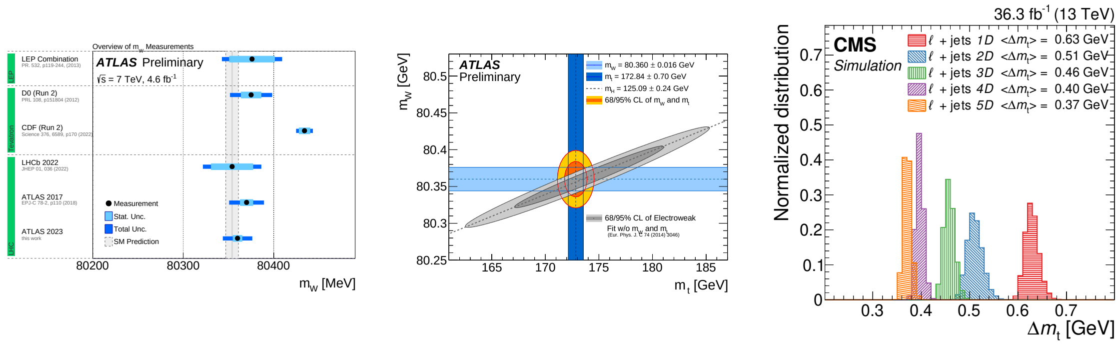

Figure 4: Left: Overview of recent W mass measurements [23]; Centre: Compatibility of W/top mass and EWK global fit [23] Right: Reduction of uncertainties by adding additional constraining dimensions to top-quark mass measurement [24]

4. W and Top Quark Mass Measurements

The W mass measurements have been intensely discussed since last year with the CDF and LHCb measurements. There is now a whole array of efforts by the LHC experiments to further improve the precision. The latest update is an ATLAS result [23] that reanalyses the dataset originally used for the a 2017 measurement. An advanced physics model and profile likelihood fitting are employed to reduce systematic uncertainties during the fit, leading to a W mass measurement improvement of around 15% in the uncertainty with respect to the previous result. A comparison with previous results and overall compatibility of the new result with the global EW fit are shown in Figure 4. At the time of the conference, the world W-mass combination became available [25]. The combinations were also performed by removing each measurement individually; a high probability of compatibility is observed when removing the CDF measurement from the combination. New measurements with improved precision are expected from the LHC experiments.

Top quark mass measurements were also briefly discussed, but the situation has not changed significantly since the previous year: The direct measurement with the highest precision is still the lepton+jets 5D profile likelihood and kinematic fit measurement by CMS at 13 TeV [24]. It has 0.2% relative uncertainty and provides strong constraints on various experimental and theoretical uncertainties as part of the fit as shown in Figure 4.

5. Top Quark Physics

The study of top quarks made a head-start in Run 3, already adding the first public result on $t\bar{t}$ cross sections at 13.6 TeV in September 2022. These early results, namely a $t\bar{t}$ cross-section measurement by CMS [26] and a top and Z cross section measurement by ATLAS come with a remarkable precision, already, and are consistent with high order predictions, see Figure 5.

In the ongoing effort towards achieving even better precision, a dilepton $e\mu$ cross section measurement by ATLAS reaches an uncertainty of 1.8% [27], see Figure 5. This achievement is enabled also thanks to the updated luminosity determination for the corresponding Run 2 dataset [28]. This example underlines the importance of continued careful studies of reconstruction performance and

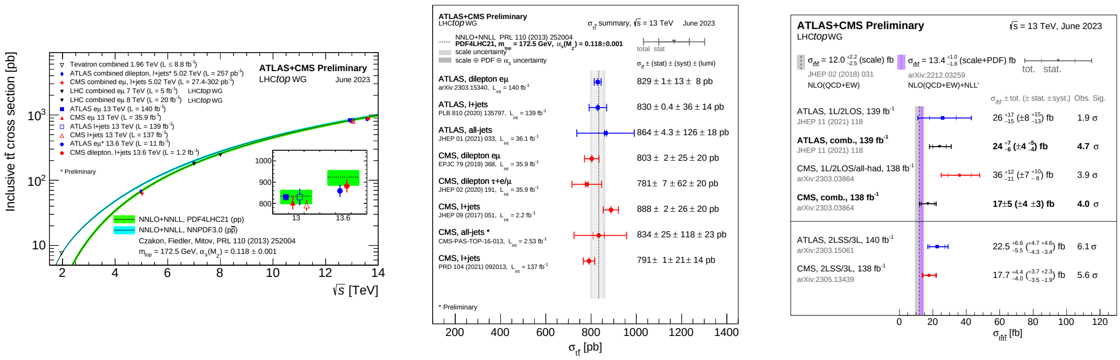

Figure 5: Summary plots of status of $t\bar{t}$ and $t\bar{t}t\bar{t}$ cross-section measurements, taken from [LHCTopWG]

detector response leading to the use of improved algorithms and methods and ultimately benefiting the precision of physics measurements.

The study of 4-top production, which probes important couplings and could see large enhancement in many BSM scenarios, has seen a lot of progress in 2023. The same-sign and multilepton channels which were released in a first iteration earlier and have the highest sensitivity were reanalized and lead to observation by both ATLAS and CMS [2, 3], see Figure 5 for a summary.

This has been the result of dedicated efforts to maximize acceptance, loosening the requirement on p_{T} thresholds for selection of objects while adopting improved object identification algorithms, and introducing intricate ways to improve the background separation and to have control of the backgrounds. Machine learning plays an important role in boosting the overall sensitivity. In support of four top and $t\bar{t}H$ analyses, a recent measurement of inclusive and differential cross sections of the $t\bar{t}b\bar{b}$ process was also presented [29].

6. Diboson, Triboson, and more Rare Processes

This section focuses on recent advancements in the study of multi-boson interactions within the SM. It encompasses analyses of diboson and triboson productions(VV/Vγ/$\gamma\gamma$ or VVV with V=W,Z), along with other rare processes. These play an important role in probing the non-abelian structure of the SM at high energy and are sensitive to new physics via anomalous Triple and Quartic Gauge Couplings (aTGC and aQGC).

Starting with diboson results, there is an extensive measurement campaign by ATLAS and CMS that probes all of the possible combinations of bosons, but also is extensive in covering different decay channels. An excellent agreement with NNLO predictions is observed for diboson measurements, when there used to be sizeable differences for comparisons with NLO. Latest results in this area have been a WW cross section measurement by ATLAS [30] and the measurement of differential ZZ+jets production cross sections by CMS [31].

Triboson and vector boson scattering processes are significantly more rare than diboson production, so that some "SM discoveries" have been made only recently or are still to be made. In a slight rephrase of the introductory words, yesterday's rare processes are the precision physics of today can be said to some of these processes by now: Vector boson scattering takes a special role as it is so closely related to the electroweak symmetry breaking and also comes with the signature

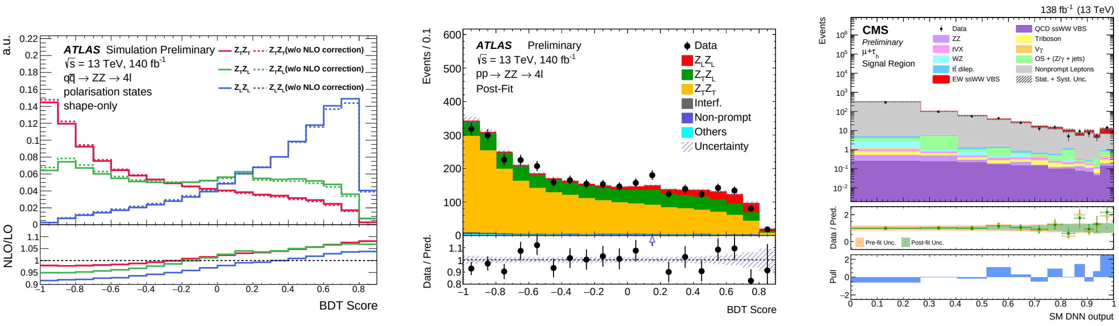

Figure 6: Left: Templates for distinguishing polarization states in [32]; Centre: Fit of different polarization states in data [32]; Right: Discriminator dsitribution of first same-sign VBS analysis with hadronic tau [33]

of two forward tag jets and the more central decay products of the gauge boson decays. First milestones and observations were reported in 2018/2019. By now many more boson combinations have been established and even more rare processes and previously unexplored decay channels become accessible. A growing focus here is to map out polarisation. For example, evidence is reported for longitudinally polarised ZZ production in a recent study by ATLAS [32]. In this analysis, a BDT is used to distinguish the different polarisation state combinations, using only angular observables to avoid the modelling uncertainties of kinematic observables. The shape of the discriminator as well as the corresponding distribution in data leading to the evidence is shown in Figure 6. A previously uncovered decay channel for same-sign VBS, namely with a hadronic tau lepton, is explored in [33] with discriminator distribution shown in Figure 6, getting close to establishing evidence with this first result.

Triboson final states have a small cross section, and only started being accessible with full Run 2 data at the LHC. The list of all observations is still reasonably short. After first establishing VVV production in 2020 [34], WWW [35], $Z\gamma\gamma$ [36], $WW\gamma$ [5], $W\gamma\gamma$ [7], and $WZ\gamma$ [6] have been established, with the latter three just this year.

Both experiments are efficiently exploiting the Run 2 data and important VBS/triboson results are public or becoming public during this period of time. This means that some of the measurements that were initially only expected to be feasible with the much larger datasets available during HL-LHC have become feasible much earlier than anticipated in initial projections.

Effective Field Theory interpretations are standard practice in SM measurements, but there is a trend further towards more global combinations, as also became evident during other presentations at the conference. Two developments worth highlighting in particular are on one hand the advanced EFT analysis in top final states presented by CMS [37] which uses event weights in simulation to achieve a transparent propagation of changes in the operators to the detector level, and on the other hand the global SMEFT interpretation by ATLAS [38] that combines Higgs boson and electroweak data from ATLAS with EW precision observable constraints from LEP and SLC.

7. Conclusions

Fueled by improved detector performance, experimental methods, and extensive data from the LHC, recent results in SM have become increasingly precise, often beyond earlier expectations.

These developments, along with theoretical progress, have enabled rigorous testing of the SM.

Precise, differential measurements over wide kinematic ranges have been performed and a number of "fundamental firsts" in multiboson studies have been achieved within the last year. Reducing systematic uncertainties, both on the experimental and on the theory side, is a challenge to stay as the datasets grow, but there has also been a lot of progress in the fruitful collaboration between experimentalists and theorists.

Many new measurement ideas and methods emerge that are pursued with existing data, already, but also profit from the ongoing data-taking during Run 3 and the extensive detector upgrades for HL-LHC, bolstering the capabilities of the experiments. Precision measurements and their global interpretation are key to a better understanding until which point the SM describes our world and pave the way towards future research at colliders and beyond.

References

[1] ATLAS Collaboration, *Measurement of the total cross section and ρ parameter from elastic scattering in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, *Eur. Phys. J. C 83 (2023) 441* (2022) [2207.12246].

[2] ATLAS Collaboration, *Observation of four-top-quark production in the multilepton final state with the ATLAS detector*, *Eur. Phys. J. C 83 (2023) 496* (2023) [2303.15061].

[3] CMS Collaboration, *Observation of four top quark production in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, *Phys. Lett. B 847 (2023) 138290* (2023) [2305.13439].

[4] ATLAS Collaboration, *Observation of single-top-quark production in association with a photon using the ATLAS detector*, *Phys. Rev. Lett. 131, (2023) 181901* (2023) [2302.01283].

[5] CMS Collaboration, *Observation of WWγ production and search for Hγ production in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, 2310.05164.

[6] ATLAS Collaboration, *Observation of $WZ\gamma$ production in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, 2305.16994.

[7] ATLAS collaboration, *Observation of W$\gamma\gamma$ triboson production in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, 2308.03041.

[8] CMS collaboration, *Evidence for tWZ production in proton-proton collisions at $\sqrt{s}$ = 13 TeV in multilepton final states*, Tech. Rep. CMS-PAS-TOP-22-008, CERN, Geneva (2023).

[9] ATLAS Collaboration, *Inclusive-photon production and its dependence on photon isolation in pp collisions at $\sqrt{s}$ = 13 TeV using 139 fb^{-1} of ATLAS data*, *JHEP07(2023)086* **2023** (2023) [2302.00510].

[10] CMS Collaboration, *Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, *JHEP 02 (2022) 142; JHEP 12 (2022) 035* (2021) [2111.10431].

[11] CMS collaboration, *Measurement of the primary Lund jet plane density in proton-proton collisions at* $\sqrt{s} = 13$ TeV, Tech. Rep. CMS-PAS-SMP-22-007, CERN, Geneva (2023).

[12] The H1 Collaboration, V. Andreev, M. Arratia, A. Baghdasaryan, A. Baty, K. Begzsuren et al., *Unbinned Deep Learning Jet Substructure Measurement in High* Q^2 *ep collisions at HERA*, *PLB 844 (2023) 138101* **844** (2023) 138101 [2303.13620].

[13] CMS collaboration, *Measurement of azimuthal correlations among jets and determination of the strong coupling in pp collisions at* $\sqrt{s} = 13$ TeV, Tech. Rep. CMS-PAS-SMP-22-005, CERN, Geneva (2023).

[14] ATLAS Collaboration, *Determination of the strong coupling constant from transverse energy−energy correlations in multijet events at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, *JHEP 07 (2023) 85* **2023** (2023) [2301.09351].

[15] CMS collaboration, *Measurement of energy correlators inside jets and determination of the strong coupling constant*, Tech. Rep. CMS-PAS-SMP-22-015, CERN, Geneva (2023).

[16] ATLAS Collaboration, *A precise measurement of the Z-boson double-differential transverse momentum and rapidity distributions in the full phase space of the decay leptons with the ATLAS experiment at* $\sqrt{s} = 8$ *TeV*, 2309.09318.

[17] F.A. Dreyer, G.P. Salam and G. Soyez, *The Lund Jet Plane*, *Journal of High Energy Physics* **2018** (2018) [1807.04758].

[18] LHCb Collaboration, R. Aaij, A.S.W. Abdelmotteleb, C.A. Beteta, F. Abudinén, T. Ackernley et al., *Measurement of Z boson production cross-section in* pp *collisions at* $\sqrt{s} = 5.02$ *TeV*, 2308.12940.

[19] ATLAS collaboration, *Precise measurements of W and Z transverse momentum spectra with the ATLAS detector at* $\sqrt{s} = 5.02$ *TeV and* 13 *TeV*, Tech. Rep. ATLAS-CONF-2023-028, CERN, Geneva (2023).

[20] CMS collaboration, *Measurement of W and Z boson inclusive cross sections in pp collisions at 5.02 and 13 TeV*, Tech. Rep. CMS-PAS-SMP-20-004, CERN, Geneva (2023).

[21] LHCb Collaboration, R. Aaij, A.S.W. Abdelmotteleb, C.A. Beteta, F. Abudinén, T. Ackernley et al., *Precision measurement of forward Z boson production in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, *JHEP 07 (2022) 026* **2022** (2021) [2112.07458].

[22] CMS collaboration, *Measurement of the inclusive cross section of Z boson production in pp collisions at* $\sqrt{s} = 13.6$ TeV, Tech. Rep. CMS-PAS-SMP-22-017, CERN, Geneva (2023).

[23] ATLAS collaboration, *Improved W boson Mass Measurement using 7 TeV Proton-Proton Collisions with the ATLAS Detector*, Tech. Rep. ATLAS-CONF-2023-004, CERN, Geneva (2023).

[24] CMS Collaboration, *Measurement of the top quark mass using a profile likelihood approach with the lepton+jets final states in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, 2302.01967.

[25] S. Amoroso, N. Andari, W. Barter, J. Bendavid, M. Boonekamp, S. Farry et al., *Compatibility and combination of world W-boson mass measurements*, 2308.09417.

[26] CMS Collaboration, *First measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s}$ = 13.6 TeV*, *JHEP 08 (2023) 204* **2023** (2023) [2303.10680].

[27] ATLAS Collaboration, *Inclusive and differential cross-sections for dilepton $t\bar{t}$ production measured in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, *JHEP07(2023)141* **2023** (2023) [2303.15340].

[28] ATLAS Collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, *Eur. Phys. J. C 83 (2023) 982* (2022) [2212.09379].

[29] CMS Collaboration, *Inclusive and differential cross section measurements of* $\mathrm{t\bar{t}b\bar{b}}$ *production in the lepton+jets channel at $\sqrt{s}$ = 13 TeV*, 2309.14442.

[30] ATLAS collaboration, *Measurements of W^+W^- production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Tech. Rep. ATLAS-CONF-2023-012, CERN, Geneva (2023).

[31] CMS collaboration, *Measurement of the differential ZZ+jets production cross sections in pp collisions at $\sqrt{s} = 13$ TeV*, Tech. Rep. CMS-PAS-SMP-22-001, CERN, Geneva (2023).

[32] ATLAS Collaboration, *Evidence of pair production of longitudinally polarised vector bosons and study of CP properties in $ZZ \to 4\ell$ events with the ATLAS detector at $\sqrt{s} = 13$ TeV*, 2310.04350.

[33] CMS collaboration, *Measurement of* $\mathrm{W^\pm W^\pm}$ *scattering in proton-proton collisions at $\sqrt{s} = 13$ TeV in final states with one tau lepton*, Tech. Rep. CMS-PAS-SMP-22-008, CERN, Geneva (2023).

[34] CMS Collaboration, *Observation of the production of three massive gauge bosons at $\sqrt{s}$ = 13 TeV*, *Phys. Rev. Lett. 125, 151802 (2020)* **125** (2020) 151802 [2006.11191].

[35] The ATLAS Collaboration, *Observation of WWW Production in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, *Phys. Rev. Lett. 129 (2022) 061803* **129** (2022) 061803 [2201.13045].

[36] ATLAS Collaboration, *Measurement of $Z\gamma\gamma$ production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Eur. Phys. J. C 83 (2023) 539* (2022) [2211.14171].

[37] CMS Collaboration, *Search for physics beyond the standard model in top quark production with additional leptons in the context of effective field theory*, 2307.15761.

[38] ATLAS collaboration, *Combined effective field theory interpretation of Higgs boson and weak boson production and decay with ATLAS data and electroweak precision observables*, Tech. Rep. ATL-PHYS-PUB-2022-037, CERN, Geneva (2022).