The Compact Muon Solenoid Experiment

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Standard Model physics results from ATLAS and CMS

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Abstract

The most recent results of Standard Model physics studies in proton-proton collisions at 7 TeV and 8 TeV center-of-mass energy based on data recorded by ATLAS and CMS detectors during the LHC Run I are reviewed. This overview includes studies of vector boson production cross section and properties, results on V+jets production with light and heavy flavours, latest VBS and VBF results, measurement of diboson production with an emphasis on ATGC and QTGC searches, as well as results on inclusive jet cross sections with strong coupling constant measurement and PDF constraints. The outlined results are compared to the prediction of the Standard Model.

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The most recent results of Standard Model physics studies in proton-proton collisions at 7 TeV and 8 TeV center-of-mass energy based on data recorded by ATLAS and CMS detectors during the LHC Run I are reviewed. This overview includes studies of vector boson production cross section and properties, results on V+jets production with light and heavy flavours, latest VBS and VBF results, measurement of diboson production with an emphasis on ATGC and AQGC searches, as well as results on inclusive jet cross sections with strong coupling constant measurement and PDF constraints. The outlined results are compared to the prediction of the Standard Model.

Keywords: Standard Model; ATLAS; CMS; LHC Run I; cross section; limits.

1. Introduction

Standard Model (SM) results from ATLAS and CMS using the LHC Run I data have given us a possibility to perform extensive tests of the electroweak and strong interaction. The most recent results of SM physics are presented in this overview.

2. Vector boson studies

2.1. The W and Z boson production

The CMS Collaboration has performed a measurement¹ of the inclusive W and Z cross sections at $\sqrt{s} = 8$ TeV as an important test of the perturbative QCD (pQCD). A low pileup sample with an average of 4 interactions per bunch crossing was used. The W boson yields were extracted from missing transverse energy (MET) distributions using a binned maximum-likelihood fit and the Z boson yield was measured by counting events in the m_{ll} window, as shown in Figure 1. The measured cross sections are in a good agreement with the NNLO QCD prediction.

The ATLAS Collaboration performed a measurement² of the Z/γ^* boson p_T distribution at 7 TeV as a traditional probe of strong interaction dynamics. The transverse momentum spectrum was measured with fine binning in both electron and muon channels, inclusive in rapidity and also in three rapidity ranges. The measured cross section was compared to pQCD and resummed predictions from FEWZ³⁻⁵, DNNLO^{6,7} and RESBOS^{8,9} at NLO+NNLL and to different generators. The measurements^{2,13} of p_T^Z and ϕ_η^* were used to tune PYTHIA8^{10,11} and POWHEG¹²+PYTHIA8 generators and found to be consistent.

Fig. 1. (a) The W boson MET distribution. (b) The m_{ll} distribution of Z candidates.

The CMS Collaboration has measured¹⁴ the Z/γ^* p_T distribution at 8 TeV. The overall agreement with the SM is observed but neither model reproduces well the p_T distribution in the accessible range.

The fiducial Drell-Yann (DY) to muons cross section at Z peak, double differentially in $p_T(Z)$ and $Y(Z)$, was measured¹⁵ by the CMS Collaboration. Production of Z boson at high $p_T(Z)$ is dominated by gluon-quark production, useful for gluon PDF constraints in $gg \rightarrow H$ process. Comparison with MADGRAPH¹⁶ and RESBOS show that both generators overshoot the data by 10 to 20% for $p_T > 120$ GeV.

The measurements of Z/γ^* boson p_T distribution are used for tuning the hadronic recoil in $W \rightarrow \mu\nu$ events, which is important for the W mass measurement.

The high p_T $Z \rightarrow b\bar{b}$ production at 8 TeV, a process that is important for high p_T $H \rightarrow b\bar{b}$ and searches for ZZ , ZH and HH ($b\bar{b}b\bar{b}$) resonances, was observed¹⁷ by the ATLAS Collaboration. The dominant background is QCD multijet, with smaller contributions from $t\bar{t}$, $Z \rightarrow c\bar{c}$ and $W \rightarrow q\bar{q}$. Two event sets are defined, corresponding to Signal (SR) and Control Region (CR). Two variables, η_{dijet} and $\Delta\eta(\text{dijet}, \text{balancing jet})$, were used as an input to the neural network. The signal was extracted by fitting simultaneously the m_{dijet} distribution of the SR and CR using a binned extended maximum likelihood (EML) fit.

2.2. Drell-Yan differential cross sections

The Drell-Yan differential cross section at 7 TeV was measured¹⁸ by the ATLAS Collaboration in the range of $116 < m_{ee} < 1500$ GeV. The Monte Carlo (MC) predictions are consistent with the shape of measured m_{ee} distribution. Measurement was extended¹⁹ down to 12 GeV using the 2010 data. POWHEG NLO+LLPS and FEWZ NNLO describe the data well, while the FEWZ NLO is less compatible.

Measurement²⁰ of the (double) differential Drell-Yan cross section at 7 TeV in a wide m_{ll} range was done by the CMS Collaboration. Differential cross section,

$d\sigma/dm$, measured in the ee and $\mu\mu$ channels, was normalized to the Z peak region. The results are in agreement with the SM prediction at NNLO. Measurement of $d^2\sigma/dmd|y|$ is compared to the FEWZ N(N)LO prediction using the CT10²¹ PDFs.

3. Vector boson + jets studies

3.1. V +Jets differential cross sections

The ATLAS Collaboration measured²² Z+jets cross section as a function of the inclusive and exclusive jet multiplicities and differential cross sections as function of jet p_T and η . The MC@NLO²³ generator fails to model higher jet multiplicities and leading jet p_T , as shown in Figure 2(a). Fixed order ME+PS (Matrix Element, Parton Shower) predictions are consistent with the measurement over a large kinematic range. The scalar p_T sum of jets (S_T) and scalar p_T sum of leptons and jets (H_T) predicted by BLACKHAT+SHERPA²⁴ deviate by several standard deviations from measured spectra in hard (S_T) and (H_T) regime. The Z+jets production was also measured²⁵ by the CMS Collaboration. The leading jet p_T distribution is shown in Figure 2(b). Agreement with MADGRAPH, SHERPA²⁶ and POWHEG is found.

The CMS Collaboration measured²⁷ the W+jets cross section and compared it to the predictions from several generators, normalized to the NNLO with FEWZ. The MADGRAPH and SHERPA are LO matrix-element (ME) calculations. The BLACKHAT+SHERPA gives fixed-order predictions at the level of ME partons of W+njets at NLO accuracy up to 4 jets. The SHERPA and BLACKHAT+SHERPA agree with measurement, while MADGRAPH prediction gives an over-estimate.

Fig. 2. (a) Differential cross section as a function of leading jet p_T from ATLAS and (b) CMS.

3.2. $W+D/D^*/\text{charm jet production}$

This measurement²⁸ by the CMS Collaboration provides a direct access to strange (anti)quark PDFs. The main $W+c+X$ background was estimated by exploiting the charge correlation. The shape of the MC predicted differential cross section is in a good agreement with the measurement, with the W^- yield a bit larger, as expected.

The ATLAS Collaboration measurement²⁹ of the integrated and differential cross sections for this process required either presence of a muon from semileptonic charm decay within a hadronic jet or a charged $D^{(*)}$ meson. The data is consistent with the PDF predictions, with a preference for PDFs with a $SU(3)$ light-quark sea.

3.3. $Z+b(b)$ production

The ATLAS Collaboration performed a measurement³⁰ of differential $Z+b$ and $Z+bb$ cross section as a probe of associated heavy flavour production. The MCFM³¹ (NLO production, five-flavour number scheme - 5FNS) agrees with data within the uncertainties. For the aMC@NLO³² the 5FNS scheme suits $Z+b$ process, while $Z+bb$ prefers 4FNS (four flavour numbering scheme). A good description of b-jet p_T shape by all generators, a reasonable description of data for $Z+bb$ process. The $W+b(b)$ process was studied^{33,34} by the ATLAS and CMS Collaborations as well.

3.4. Electroweak production of $WWjj$

This key process to probe³⁵ the nature of EWK symmetry was measured by the ATLAS Collaboration in the two event classes: inclusive region (strong) and VBS region (EWK, $|\Delta y_{jj}| > 2.4$). Signal is two same-sign leptons ($ee, e\mu$ and $\mu\mu$) and at least two jets. The measured fiducial cross sections for strong and VBS processes are in a good agreement with the SM prediction. An excess of events over background is observed (expected): 4.5σ (3.4σ) in the inclusive region and 3.6σ (2.8σ) in the VBS region, as shown in Figure 3(a). Limits on h_4 and h_5 AQC parameters are set in the VBS region. The confidence level contours are shown in Figure 3(b).

Fig. 3. (a) The m_{jj} distribution after the inclusive region selection. (b) Limits on (α_4, α_5) .

3.5. Electroweak Zjj production

The CMS Collaboration performed a measurement³⁶ of the fiducial cross sections and differential distributions of the inclusive Zjj , sensitive to the EWK Zjj . Observation was more than 5σ . An agreement with the SM resulted with ATGC limits.

The ATLAS Collaboration has applied two methods of EWK Zjj signal extraction³⁷: multivariate analysis, exploiting discrimination with respect to the QCD Zjj process, and data-driven prediction of QCD background based on $\gamma+jj$ sample using dijet Fisher discriminant³⁸. Results are compatible with the theoretical prediction.

4. Multiboson studies

4.1. WZ and ZZ production using $Z \rightarrow bb$ decays

Both of these processes are an important backgrounds to the associated production of Higgs and vector boson, in particular in channels involving $H \rightarrow bb$ decays. The CMS Collaboration performed the analysis³⁹ in final states with 0, 1 or 2 leptons using two methods: fit to the multivariate output and fit to the two jet mass. The total cross sections were determined from simultaneous fit to all final states. The multivariate analysis observed (expected) 6.3σ (5.9σ) and m_{bb} analysis observed (expected) 4.1σ (4.6σ). The measured cross sections agree with the SM prediction.

4.2. $ZZ \rightarrow 4l$ production

The CMS Collaboration measured⁴⁰ inclusive and differential $ZZ \rightarrow lll'l'$ cross sections ($l=e, \mu$ and $l'=e, \mu$ or τ) at 8 TeV. The exclusive sets of $4e$, 4μ , $2e2\mu$ and $ll\tau\tau$ were studied. Simultaneous fit to include all final states was performed to calculate the differential cross sections. The limits on ZZZ and $ZZ\gamma$ couplings were derived.

4.3. $Z \rightarrow 4l$ production

The inclusive $4l$ production at the Z resonance was measured⁴¹ by the ATLAS Collaboration at 7 and 8 TeV. The event selection followed closely the $H \rightarrow ZZ^* \rightarrow 4l$ analysis⁴² with $p_T(\mu)$ and m_{ll} requirements to increase the $Z \rightarrow 4l$ acceptance. The $\Gamma(Z \rightarrow 4l)$ was determined by subtracting the non-resonant $4l$ contributions and normalising the resulting yield to the observed number of the $Z \rightarrow \mu\mu$ events in the same dataset. The CMS Collaboration has also measured⁴³ this process at 7 TeV.

4.4. Anomalous triple and quartic couplings

The most recent ATLAS and CMS Collaborations limits on charged^{44–51}, $WW\gamma$ and WWZ and neutral^{44,52–57}, $ZZ\gamma$ and $Z\gamma\gamma$ ATGCs are approaching the sensitivity of LEP⁴⁹, some are world-best. The $Z\gamma\gamma$ limits from CMS are shown in Figure 4(a).

Two photon production of a pair of W bosons is sensitive to AQGCs. Limits⁵⁸ set by the CMS Collaboration are two orders of magnitude more stringent than the

LEP limits⁵⁹ and around 20 times better than Tevatron results⁶⁰, shown in Figure 4(b). Search for AQGCs through the $WV\gamma$ state, where W boson decays to leptons and $V(W \text{ or } Z)$ to jets, presented the first limits⁶¹ on anomalous $WWZ\gamma$ couplings.

Fig. 4. (a) Exclusion contours for $Z\gamma\gamma$ process. (b) The limits on $\gamma\gamma WW$ ATGCs

5. Jet physics studies

5.1. Jet production cross sections

The ATLAS Collaboration measured⁶² double differential cross sections at 7 TeV as a function of m_{jj} up to 5 TeV and separation of two leading p_T jets up to $y^* < 3.0$ (Figure 5(a)). Improved measurement for high m_{jj} can be used to constrain gluon PDFs at high momentum fraction. Good agreement for CT10, NNPDF2.1^{63,64} and MSTW 2008⁶⁵ PDF, disagreement for HERAPDF1.5⁶⁶ and NLOJet++⁶⁷ with ABM11⁶⁸. The CMS Collaboration has performed this measurement⁶⁹ at 8 TeV.

Inclusive jet cross sections, double-differential in jet p_T up to 2.5 TeV and $|y|$ up to 3.0, were measured⁷⁰ by the CMS Collaboration at 8 TeV. The pQCD describes data well in a wide range of p_T and $|y|$. Good agreement was found in low p_T region, except for ABM11 PDF. In high p_T region only the CT10 agrees with data. The ATLAS Collaboration has also a measurement⁷¹ of the ratio of the inclusive jet cross sections at 2.76 TeV to the inclusive jet cross section results at the 7 TeV.

5.2. Constraints on PDFs and α_s

The impact of the inclusive jet cross section measurements on the proton PDFs was studied⁷². Adding the CMS inclusive jet data have significantly reduced the uncertainty on gluon distribution for the fractional parton momenta of $x \geq 0.01$.

Strong coupling constant was fitted as a free parameter in addition to PDFs using CMS data (Figure 5(b)). Results are consistent with dedicated fits of strong constant: $\alpha_s(M_Z) = 0.1185 \pm 0.0019(\text{exp.}) \pm 0.0028(\text{PDF}) \pm 0.0004(\text{NP})_{-0.0022}^{+0.0055}(\text{scale})$.

Fig. 5. (a) Dijet double-differential cross sections as a function of dijet mass in different ranges of y^* (ATLAS). (b) The strong coupling $\alpha_s(Q)$ (solid line) and its total uncertainty (band) (CMS).

6. Conclusions

Studies of the vector boson production showed unprecedented precision and enabled testing of the pQCD over large kinematic region never probed before. Measurements of the V+jets production improved, the pQCD predictions were confirmed. The multiboson studies resulted with limits reaching the sensitivity of LEP, several being world-leading. Inclusive jet cross sections were measured in the extended phase space, reducing the uncertainty on PDFs, strong coupling constant was measured.

References

1. S. Chatrchyan et al. (CMS Collaboration), *Phys. Rev. Lett.* **112**, 191802, (2014).
2. G. Aad et al. (ATLAS Collaboration), arXiv:1406.3660v1.
3. K. Melnikov and F. Petriello, Electroweak gauge boson production at hadron colliders through $\mathcal{O}(\alpha_s^2)$, *Phys. Rev. D* **74**, 114017, (2006).
4. R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, Fewz 2.0, A code for hadronic Z production at next-to-next-to-leading order, *Comput. Phys. Commun.* **182**, 2388-2403, (2011).
5. Y. Li and F. Petriello, Combining QCD and electroweak corrections to dilepton production in FEWZ, *Phys. Rev. D* **86**, 094034, (2012).
6. S. Catani, L. Cieri, G. Ferrera, D. de Florian, and M. Grazzini, Vector boson production at hadron colliders: a fully exclusive QCD calculation at NNLO, *Phys. Rev. Lett.* **103**, 082001, (2009).
7. S. Catani and M. Grazzini, An NNLO subtraction formalism in hadron collisions and its application to Higgs boson production at the LHC, *Phys. Rev. Lett.* **98**, 222002, (2007).
8. C. Balazs and C. Yuan, Soft gluon effects on lepton pairs at hadron colliders, *Phys. Rev. D* **56**, 5558-5583, (1997).
9. M. Guzzi, P. M. Nadolsky, and B. Wang, Nonperturbative contributions to a resummed leptonic angular distribution in inclusive neutral vector boson pro-

- duction, arXiv:1309.1393.
10. T. Sjöstrand, S. Mrenna and P. Skands, *JHEP* **05**, 026, (2006).
 11. T. Sjöstrand, S. Mrenna and P. Skands, *Comput. Phys. Comm.* **178**, 852, (2008).
 12. S. Alioli, P. Nason, C. Oleari, and E. Re, NLO vector-boson production matched with shower in POWHEG, *JHEP* **07**, 060, (2008).
 13. G. Aad et al. (ATLAS Collaboration), *Phys. Lett. B* **720**, 32-51, (2013).
 14. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-12-025, (2013).
 15. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-13-013, (2014).
 16. J. Alwall et al., MadGraph 5 : going beyond, *JHEP* **1106** (2011).
 17. G. Aad et al. (ATLAS Collaboration), arXiv:1404.7042v1.
 18. G. Aad et al. (ATLAS Collaboration), *Phys. Lett. B* **725**, 223-242, (2013).
 19. G. Aad et al. (ATLAS Collaboration), arXiv:1404.1212.
 20. S. Chatrchyan et al. (CMS Collaboration), *JHEP* **12**, 030, (2013).
 21. H.-L. Lai et al., New parton distributions for collider physics, *Phys. Rev. D* **82**, 074024 (2010).
 22. G. Aad et al. (ATLAS Collaboration), arXiv:1304.7098v1.
 23. S. Frixione and B. R. Webber, Matching NLO QCD Computations and Parton Shower Simulations, *JHEP* **0206**, 029, (2002).
 24. C. F. Berger et al., Next-to-Leading Order QCD Predictions for W+3-Jet Distributions at Hadron Colliders, *Phys. Rev. D* **80**, 074036 (2009).
 25. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-12-017, (2014).
 26. T. Gleisberg et al., Event Generation with SHERPA 1.1, *JHEP* **02**, 007, (2009).
 27. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-12-023, (2014).
 28. S. Chatrchyan et al. (CMS Collaboration), arXiv:1310.1138v2.
 29. G. Aad et al. (ATLAS Collaboration), arXiv:1402.6263v1.
 30. G. Aad et al. (ATLAS Collaboration), arXiv:1407.3643.
 31. J. M. Campbell and R. Ellis, MCFM for the Tevatron and the LHC, *Nucl. Phys. Proc. Suppl.* **205-206**, 10, (2010).
 32. J. Alwall et al., The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, arXiv:1405.0301.
 33. S. Chatrchyan et al. (CMS Collaboration), *Phys. Lett. B* **735**, 204-225, (2013).
 34. G. Aad et al. (ATLAS Collaboration), *JHEP* **06**, 084, (2013).
 35. G. Aad et al. (ATLAS Collaboration), arXiv:1405.6241v1.
 36. S. Chatrchyan et al. (CMS Collaboration), CMS PAS FSQ-12-035, (2014).
 37. G. Aad et al. (ATLAS Collaboration), arXiv:1401.7610v2.
 38. R. Fisher, The use of multiple measurements in taxonomic problems, *Annals of Eugenics* **7**, no. 2, 179-188(1936).
 39. S. Chatrchyan et al. (CMS Collaboration), arXiv:1403.3047v1.
 40. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-13-005, (2014).
 41. G. Aad et al. (ATLAS Collaboration), *Phys. Rev. Lett.* **112**, 231806 (2014).
 42. G. Aad et al. (ATLAS Collaboration), *Phys. Lett. B* **726**, 88, (2014).

43. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-12-009, (2014).
44. G. Aad et al. (ATLAS Collaboration), *Phys. Rev. D* **87**,112003, (2013).
45. S. Chatrchyan et al. (CMS Collaboration), arXiv:1308.6832v2.
46. S. Chatrchyan et al. (CMS Collaboration), *Eur. Phys. J. C* **73**, 2610, (2013).
47. S. Chatrchyan et al. (CMS Collaboration), *Eur. Phys. J. C* **73**, 2283, (2013).
48. V.M. Abazov et al. (D0 Collaboration), *Phys. Lett. B* **718**, 451-459, (2012).
49. The ALEPH Collaboration, The DELPHI Collaboration, The L3 Collaboration, The OPAL Collaboration, The LEP Electroweak Working Group, *Physics Reports*, **532**, 4, (2013).
50. G. Aad et al. (ATLAS Collaboration), *Phys. Rev. D* **87**,112001, (2013).
51. G. Aad et al. (ATLAS Collaboration), *Eur. Phys. J. C* **72**, 2173, (2013).
52. S. Chatrchyan et al. (CMS Collaboration), arXiv:1308.6832v2.
53. S. Chatrchyan et al. (CMS Collaboration), *JHEP* **10**, 164, (2013).
54. T. Aaltonen, et al. (CDF Collaboration), *Phys. Rev. Lett.* **107**, 051802, (2011).
55. G. Aad et al. (ATLAS Collaboration), *JHEP* **03**, 128, (2013).
56. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-13-005, (2013).
57. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-13-016, (2013).
58. S. Chatrchyan et al. (CMS Collaboration), *JHEP* **07**, 116, (2013).
59. P. Achard et al. (L3 Collaboration), *Phys. Lett. B* **527**, 29-38, (2002).
60. V.M. Abazov et al. (D0 Collaboration), *Phys. Rev. D* **88**, 012005, (2013).
61. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-13-019, (2013).
62. G. Aad et al. (ATLAS Collaboration), *JHEP* **05**, 059, (2014).
63. R. Ball et al., A first unbiased global NLO determination of parton distributions and their uncertainties, *Nucl. Phys. B* **838**, 136-206, (2010).
64. S. Forte, E. Laenen, P. Nason, and J. Rojo, Heavy quarks in deep-inelastic scattering, *Nucl. Phys. B* **834**, 116-162, (2010).
65. A. Martin, W. Stirling, R. Thorne, and G. Watt, Parton distributions for the LHC, *Eur. Phys. J. C* **63**, 189-285, (2009).
66. H1 and ZEUS Collaborations, HERAPDF 1.5, H1prelim-10-142, ZEUS-prelim-10-018.
67. Z. Nagy, Next-to-leading order calculation of three jet observables in hadron hadron collision, *Phys. Rev. D* **68**, 094002, (2003).
68. S. Alekhin, J. Bluemlein, and S.-O. Moch, ABM11 PDFs and the cross section benchmarks in NNLO, *PoS LL* **2012**, 016, (2012).
69. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-14-002, (2013).
70. S. Chatrchyan et al. (CMS Collaboration), CMS PAS SMP-12-012, (2013).
71. G. Aad et al. (ATLAS Collaboration), arXiv:1304.4739v2, (2013).
72. S. Chatrchyan et al. (CMS Collaboration), *Eur. Phys. J. C* **73**, 2604, (2013).