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Highlights from the ATLAS experiment

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An overview of recent physics analysis highlights from the ATLAS experiment is provided, with a focus on new results obtained with 13 TeV pp data taken in 2015 and 2016.

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1. Introduction

A major focus of the ATLAS [1] physics programme over the past year has been the release of the first results based on the full 2015 and 2016 13 TeV pp dataset. The results cover the full breadth of the programme, including both measurements of Standard Model (SM) processes and searches for new particles and rare processes both within and beyond the SM (BSM). Milestone results include the first evidence for Higgs boson decays to bottom quarks obtained at the LHC, the first measurement of the mass of the Higgs boson from ATLAS in Run-2, and the first evidence for single top quark production in association with a Z boson. Analysis of Pb-Pb and p-Pb heavy ion collision data obtained in 2015 and 2016 respectively has also yielded important new insights, including evidence for light-by-light scattering in 5.02 TeV Pb-Pb collisions.

In addition, a number of important new results obtained with Run-1 data have also been released, including the world's most precise measurement of the top quark pole mass, obtained from differential measurements of lepton production in top quark pair events at 8 TeV. A major highlight is the first measurement of the mass of the W boson obtained at the LHC – a milestone for the ATLAS physics programme.

In parallel to these activities ATLAS has completed preparations for analysis of 2017 data, including reprocessing of the complete 2015+2016 dataset with new, more performant, reconstruction software, and production of more than five billion Monte Carlo events with new simulation software with refined detector geometry and physics list.

Only a small fraction of the many ATLAS physics results released over the past year can be summarised in a short document such as this. A few highlights are provided below.

2. Searches for new physics with 2015 and 2016 pp data

Searches for new particles have been conducted with many different final states. In no case has a statistically significant excess over SM expectations been found. Stringent limits have therefore been set on the properties of many different particles predicted by a wide range of new physics models.

Searches for excesses in dijet mass and angular distributions [2] have set 95% CL limits of 6.0 TeV (5.8 TeV expected) on the mass of excited quarks, 8.9 TeV (8.9 TeV expected) on the mass of quantum black holes and 21.8 TeV (28.3 TeV expected) on the scale of new left-chiral colour-singlet contact interactions with negative coupling coefficient. Searches for dilepton resonances [3] (Figure 1 (left)) have set a limit of 4.5 TeV (4.5 TeV expected) on the mass of a Z' in the Sequential Standard Model scenario, while searches for a Jacobian peak in the transverse mass distribution of lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ events [4] have set limits of 5.1 TeV (5.2 TeV expected) for the mass of a W in the same scenario.

Many searches for new resonances decaying to SM electroweak (Z/W) or Higgs boson pairs have been conducted using final states with quarks [5, 6, 7, 8, 9]. Searches for the highest mass resonances have benefited considerably from the development of jet substructure techniques for tagging merged jets from boosted hadronically decaying bosons at high p_{T}. Limits have been set on the mass of new states in the framework of Heavy Vector Triplet models, for instance with a

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mass limit of 3.5 TeV (3.1 TeV expected) for a new resonance decaying to WW and WZ final states in the HVT Model B scenario [9] (Figure 1 (right)).

Searches with diphoton final states [10] have found no evidence for new particles, under either a spin-0 (scalar) hypothesis or a spin-2 (graviton) hypothesis. Searches for tau lepton pair resonances [11] have set stringent limits on the properties of new Higgs bosons in 2HDM and SUSY models, for instance excluding $\tan\beta > 45$ for $m_A = 1.5$ TeV in the hMSSM supersymmetry scenario.

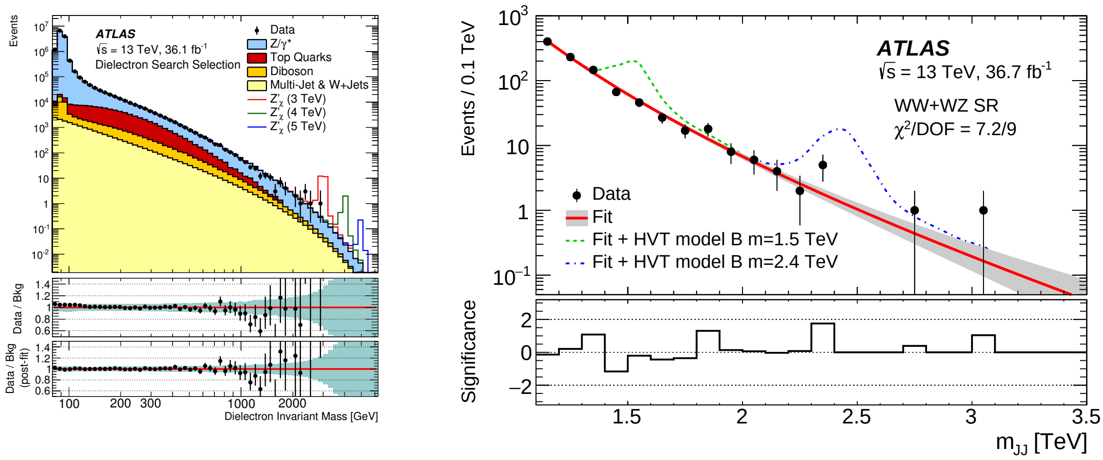

Figure 1: Dielectron invariant mass distribution from the high mass dilepton resonance search (left – taken from Ref. [3]). Invariant mass distribution of two large radius 'boson-tagged' jets in the search for resonances decaying to pairs of hadronically decaying W or Z bosons (right – taken from Ref. [9]).

Searches for the production of dark matter (DM) particles rely upon signatures in which they are produced in association with SM particles observed in the detector, leading to events with missing transverse energy plus a single reconstructed SM state. The DM particles are assumed to couple to SM particles via a new 'mediator' particle. Limits are therefore set as a function of the masses of the mediator and DM particles and of the coupling between the mediator and SM states. Searches have been performed with jets [12], photons [13], Higgs bosons [14, 15], or Z bosons [16], recoiling against $E_{\mathrm{T}}^{\mathrm{miss}}$, setting limits of, for instance 1.55 TeV (1.8 TeV expected) on the mass of an axial-vector mediator for massless Dirac DM particles and a quark-mediator coupling parameter of 0.25. In such models the coupling of the mediator to quarks enables competitive searches to also be carried out using the dijet resonance analysis described above [2]. In the case of this model the mediator mass limits from this analysis extend to 2.6 TeV for massless DM particles.

3. Searches for supersymmetry with 2015 and 2016 *pp* data

Searches for evidence of R-Parity conserving supersymmetry (SUSY) have been conducted using many different signatures. Inclusive searches for strongly interacting squarks and gluinos with jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ signatures [17] now exclude masses beyond 2.0 TeV for the first time. These searches are complemented by those which require b-tagged jets in the final state [18], targeting models in which 3rd generation squarks (top and bottom squarks) are produced in gluino cascade decays. Here, gluino mass limits approach 2.0 TeV. These limits extend up to 500 GeV beyond the most recent previously published ATLAS results obtained with the 2015 dataset.

In the absence of significant excesses in these inclusive searches, focus is increasingly being placed on searches for 'natural' SUSY models with light top and bottom squarks and light higgsinos. Searches for direct pair production of these states exploit improvements in b-tagging performance obtained from the new ATLAS Run-2 IBL detector [19], and improvements in the efficiency for reconstruction and identification of soft leptons produced in the decay of nearly mass-degenerate gauginos and higgsinos. Top squark searches (Figure 2 (left)) have been conducted using signatures with 0, 1 or 2 leptons plus b-tagged jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ [20, 21, 22], covering models in which the squarks decay via 2, 3 or 4 body modes. Bottom squark searches [23] focus on the simpler two b-jet plus $E_{\mathrm{T}}^{\mathrm{miss}}$ final state. In both cases mass limits extend to 950 GeV for massless lightest neutralino LSPs (Lightest SUSY Particle).

Searches for direct associated chargino and neutralino production have been conducted with signatures with 2 or 3 leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$ [24]. In the case of cascade decays involving sleptons the mass limits extend to 1.15 TeV for light LSPs (Figure 2 (right)). In the interesting case of direct decays from mass degenerate charginos or next-to-lightest neutralinos to the lightest neutralino LSP the mass limits extend to 580 GeV.

In addition, many searches have been conducted focusing on more challenging signatures (for instance without significant $E_{\mathrm{T}}^{\mathrm{miss}}$ or involving long-lived particles decaying in the detector) which give sensitivity to lower mass models, e.g. with R-Parity violation (e.g. Ref. [25]), which might otherwise escape detection.

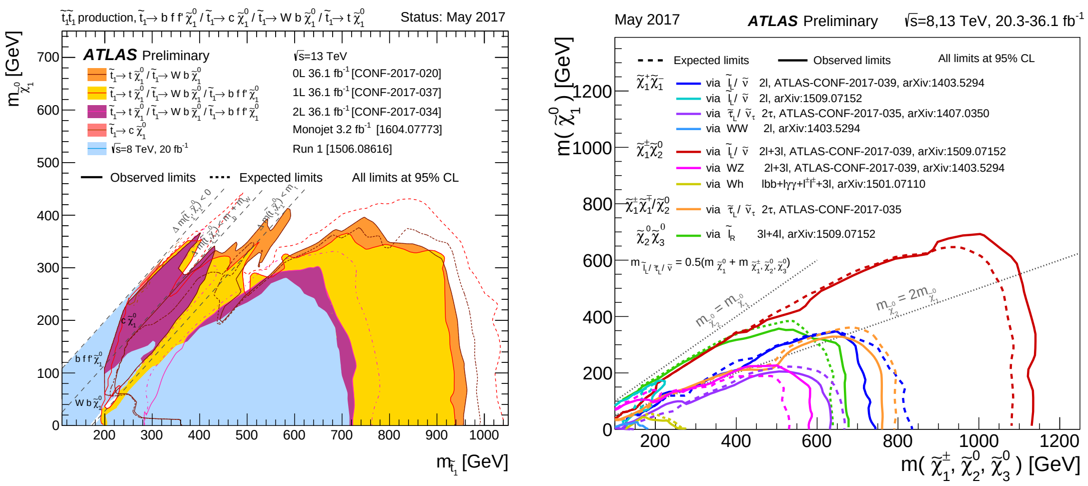

Figure 2: Limits on the mass of the SUSY top squark for various decay modes as a function of the mass of the LSP (left). Limits on the mass of mass-degenerate SUSY charginos and neutralinos for various decay modes, as a function of the mass of the LSP (right). Taken from Ref. [26].

4. Measurements of the properties of the Higgs boson with 2015 and 2016 pp data

With larger statistics and a higher centre-of-mass energy than at Run-1, new possibilities for measurements of the properties of the Higgs boson have opened up with the full 2015+2016 ATLAS dataset. The most precise measurements use the flagship $H \to ZZ^* \to 4\ell$ [27] and $H \to \gamma\gamma$ [28] channels, which also formed the basis for the discovery of the Higgs boson by ATLAS [29] and CMS [30] in 2012. Assuming SM branching ratios these channels have provided a combined measurement of the total Higgs production cross-section of $57.0 \pm 6.0_{\rm stat} \pm 3.7_{\rm syst}$ pb [31] (Figure 3 (left)), or alternatively a measurement of the Higgs signal strength $\mu = 1.09 \pm 0.12$ indicating good compatibility with the SM prediction. Measurements of cross-sections for different Higgs boson production modes (gluon-gluon fusion, vector boson fusion etc.) have also been performed, with results interpreted using the new simplified template cross-section (STXS) framework [32]. Finally, differential measurements of production cross-sections as functions of various kinematic properties (e.g. transverse momentum of the Higgs boson) have been obtained [28, 33]. All these measurements indicate good agreement with SM predictions.

The $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ channels have also provided the basis for the first ATLAS measurement of the mass of the Higgs boson obtained with Run-2 data [34]. The measurements in the two channels are complementary; the $H \to ZZ^* \to 4\ell$ channel is statistics limited while the uncertainty obtained from the $H \to \gamma\gamma$ channel is dominated by systematic uncertainties arising from the photon energy scale calibration. In the former case the measurements are consistent between sub-channels requiring electrons and/or muons, while in the latter case measurements are consistent between sub-channels categorised in terms of converted/unconverted photons or in terms of barrel/endcap photons. The measurements in the two channels are consistent within 0.4σ. The combined measurement of 124.98 ± 0.28 GeV is consistent with the combined LHC Run-1 measurement of 125.09 ± 0.24 GeV [35].

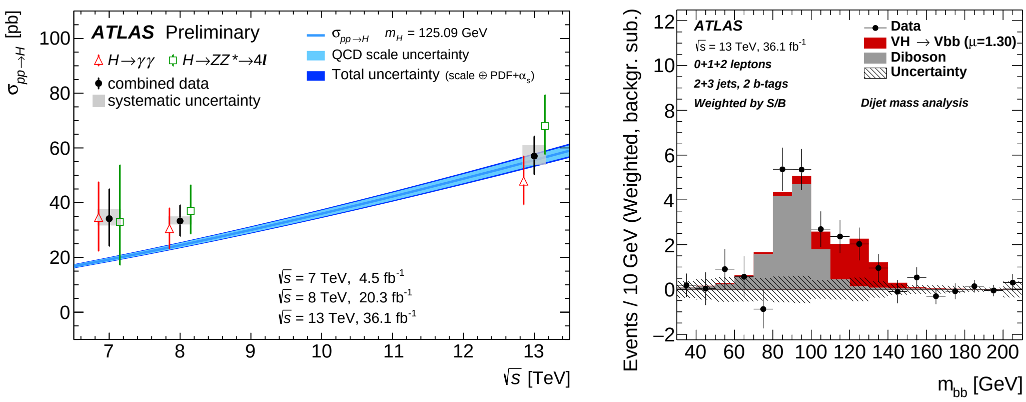

Figure 3: Measurements of the total cross-section for Higgs boson production as a function of $\sqrt{s}$ obtained from the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ channels (left – taken from Ref. [31]). Distribution of the invariant mass of b-jet pairs in the cut-based VH, $H \to b\bar{b}$ search following subtraction of all backgrounds except SM VZ production (right – taken from Ref. [36]).

Key targets of the LHC physics programme are measurements of Higgs boson couplings to fermions, which test the Yukawa sector of the SM. ATLAS has now obtained the first evidence at the LHC of Higgs boson decays to bottom quark pairs [36]. In the SM this is expected to be the most common Higgs boson decay mode (BR$\sim$58%) and hence direct measurement strongly constrains the scope for new BSM Higgs boson couplings. This decay mode is difficult to observe because of overwhelming QCD backgrounds. The most sensitive channel exploits the VH production mechanism, where the Higgs boson is produced in association with a SM W or Z boson. The ATLAS analysis combines measurements with 0, 1 and 2-lepton final states arising from $Z \to \nu\bar{\nu}$, $W \to \ell\nu$ and $Z \to \ell^+\ell^-$ decays. The primary analysis makes use of powerful multi-variate techniques based upon Boosted Decision Tree (BDT) classifiers. The analysis is cross-checked with a cut-based selection exploiting the bb invariant mass to isolate the signal. The performance of both analyses is validated with an independent, separately optimized, search for VZ, $Z \to b\bar{b}$ production. In both cases a clear VZ signal is observed (5.8σ observed, 5.3σ expected in the BDT analysis) with a signal strength (μ_{VZ} = 1.11 $\pm$ 0.24 in the BDT analysis) consistent with SM expectations. The BDT (cut-based) VH search observes an excess above the background-only hypothesis in Run-2 data with a significance of 3.5σ (3.5σ) with an expected significance of 3.0σ (2.8σ). The background-subtracted m_{bb} distribution from the cut-based analysis is shown in Figure 3 (right). Combination of the BDT result with ATLAS Run-1 data yields an excess with significance of 3.6σ (4.0σ expected). The observed signal strength of μ_{VH} = 0.90 $\pm$ 0.27 is consistent with SM expectations.

5. Measurements of (non-Higgs) SM processes with Run-2 or Run-1 pp data

A highlight of the recent ATLAS Run-1 analyses is the first measurement of the mass of the W boson performed at the LHC, which has been obtained using the 7 TeV dataset recorded in 2011 [37]. The shapes of the Jacobian peaks in the transverse momentum and transverse mass distributions of W bosons decaying to electrons or muons and neutrinos provide sensitivity to the mass of the parent W. The measurement is calibrated by comparison with similar measurements carried out with Z bosons decaying to electron or muon pairs. The analysis requires precise control of a very large number of systematic uncertainties related to both the performance of the experiment (energy scales, reconstruction efficiencies etc.) and the modelling of the W boson signal (especially the W boson p_{T} distribution relative to that of the Z boson calibration sample) and backgrounds. Following five years of intensive work a final result of $m_W = 80370 \pm 19$ MeV has been obtained, consistent with previous measurements and expectations from global fits of other measurements sensitive to electroweak physics (Figure 4). The uncertainty is equivalent to that of the most precise previous single-experiment result obtained by CDF. The uncertainty is dominated by modelling systematics (14 MeV), emphasising the importance of improvements in theoretical understanding and measurements to constrain theoretical uncertainties for future results.

A number of new measurements of top quark properties have been obtained recently. Notably, ATLAS has made important new measurements of single top quark production. Previously, ATLAS has observed or obtained evidence for single top quark production in the t-channel, s-channel and the Wt associated production modes. Now, with the full 2015+2016 ATLAS Run-2 dataset, evidence has also been obtained for Zt associated production [38]. The analysis uses sophisticated multi-variate techniques to separate the signal from the SM diboson, Z+jets and top quark pair backgrounds (Figure 5 (left)). A significance of 4.2σ (5.4σ) is observed (expected). The production cross-section is measured to be $620 \pm 170_{\mathrm{stat}} \pm 140_{\mathrm{syst}}$ fb, consistent with SM expectations.

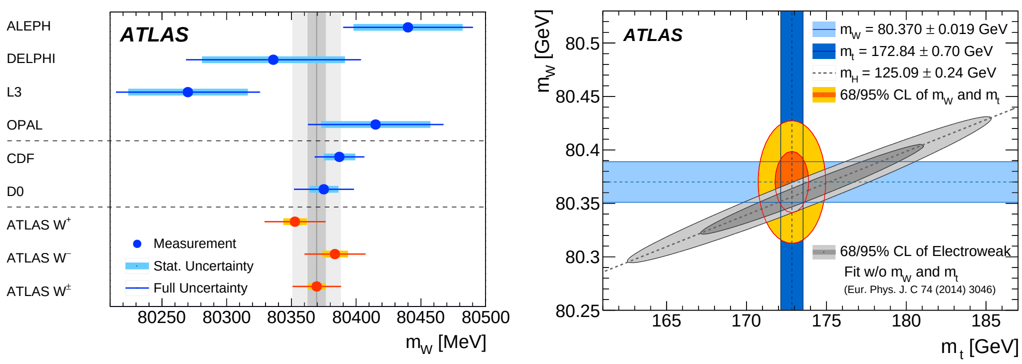

Figure 4: ATLAS measurement of the mass of the W boson compared with measurements from previous experiments (left). Comparison with results of a global electroweak fit (right). Taken from Ref. [37].

Measurements of the top quark pole mass have previously been obtained by ATLAS, as well as other experiments, by comparing inclusive or differential top quark production cross-sections with fixed-order NLO QCD calculations that use a well defined renormalisation scheme. These measurements are subject to significant theoretical uncertainties arising from modelling of hadronisation however. To mitigate this problem, ATLAS has performed a new measurement of the top quark pole mass based upon differential measurements of lepton production in top quark pair events [39]. The cross-section measurements are compared with fixed-order NLO QCD predictions to obtain a value $m_t^{\text{pole}} = 173.2 \pm 1.6$ GeV (Figure 5 (right)), consistent with the previous world-average.

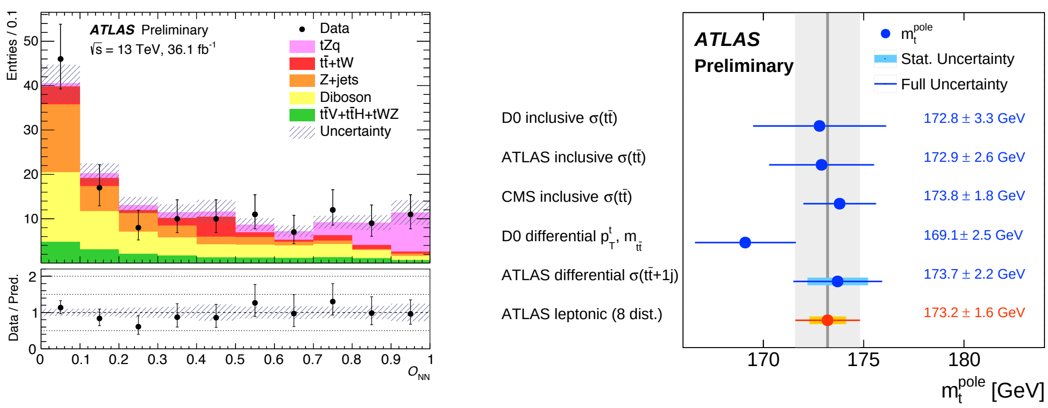

Figure 5: Neural network MVA discriminant output from the search for Zt associated single top production (left – taken from Ref. [38]). Summary of measurements of the top quark pole mass including that obtained from the ATLAS lepton differential cross-section measurement (right – taken from Ref. [39]).

An outstanding question in B-physics has been the origin of an excess in measurements of the P_5' parameter describing the angular dependence of the amplitude for B_d^0 decays to the $K^*\mu^+\mu^-$ final state observed by LHCb [40, 41] and Belle [42]. This excess with respect to the SM expectation is most prominent in events with (squared) four-momentum transfer to the muon pair of approximately 5.0 GeV^2. A new ATLAS analysis using the full 8 TeV Run-1 dataset [43] observes a value of $P_5' = 0.26 \pm 0.35_{\text{stat}} \pm 0.17_{\text{syst}}$ in this region, consistent with the SM expectation but also consistent with the LHCb and Belle results.

6. Heavy Ion physics

ATLAS has recently released first evidence for high energy light-by-light scattering (a purely QED process) in ultra-peripheral Pb-Pb collisions, based upon 5.02 TeV data recorded in 2015 [44]. In these collisions the nuclei are sufficiently well separated to strongly suppress short-range hadronic interactions, allowing the longer-range electromagnetic interactions of the highly charged ions to dominate. The resulting experimental signature is a pair of back-to-back photons with low acoplanarity (Figure 6(left)) and very little additional activity in the detector.

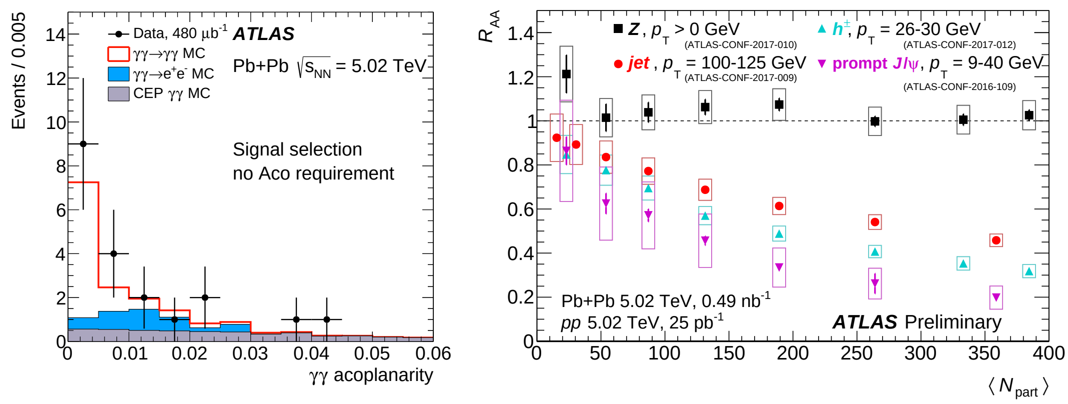

Figure 6: Distribution of acoplanarity for diphoton events selected in the search for light-by-light scattering in ultra-peripheral Pb-Pb collisions at 5.02 TeV (left – taken from Ref. [44]). Nuclear modification factor R_{AA}, measuring the relative suppression of production of a given probe in 5.02 TeV Pb-Pb collisions and pp collisions, as a function of the number of participating nucleons $\langle N_{\text{part}} \rangle$ for a variety of probes (right – taken from Ref. [45]).

New ATLAS measurements, fully corrected for detector resolution, show the suppression of jet production in central Pb-Pb and p-Pb collisions at high p_{T} and large multiplicity of participating nucleons, relative to pp collisions of the same energy (Figure 6(right)). This is interpreted as being due to strong final state interactions with the dense nuclear medium created in the collisions. Similar suppression is not observed for weakly interacting probes such as photons and Z bosons. Measurements of the suppression of colourless bound states of heavy quarks (Υ, J/ψ, $\psi(2S)$) are sensitive to the conditions present in the medium and provide important inputs to model building.

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