IL NUOVO CIMENTO **40 C** (2017) 173
DOI 10.1393/ncc/i2017-17173-7

Colloquia: LaThuile 2017

# Heavy ions at CMS

G. I. Veres(*)

*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University Budapest, Hungary*

received 16 September 2017

**Summary.** — In the present proceedings recent heavy ion results from the Compact Muon Solenoid collaboration at the LHC are presented. These contain comparisons between small and large collision systems, as well as studies of energy evolution, and thus include data collected in proton-proton collisions at 13 TeV (2015 and 2016), proton-proton and lead-lead collisions at 5 TeV (2015), and proton-lead collisions at 5 TeV and 8 TeV (2016) center-of-mass energy per nucleon pair. They provide new insights into the properties of the extremely high density and high temperature matter created in heavy ion collisions, while pointing out similarities and differences in comparison to smaller collision systems. These include gluon distribution functions in the lead nucleus; the azimuthal anisotropy of final state particle distributions in all the three different collision systems; charge separation signals from proton-lead collisions and consequences for the Chiral Magnetic Effect; new studies of parton energy loss and its dependence on parton flavor and parton shower shape; and the suppression of quarkonium states in the deconfined QCD matter.

## 1. – Introduction

Studies of the QCD matter at extremely high densities and temperature have undergone a remarkable evolution in terms of precision. The high precision achieved by the CMS experiment is truly outstanding, due to the large production cross section of various hard probes (vector bosons, high energy photons, jets, and heavy quark mesons), high luminosity as well as the high readout rate and flexible triggering capabilities.

These probes make it possible to study various properties of the large volume, high density matter created in a heavy ion collision, making use of the fact that these diagnostic tools are created simultaneously in the collision. At the same time, many of the properties of the expansion of this matter following the collision can be successfully described in terms of hydrodynamical evolution and statistical physics, however, in

(*) On behalf of the CMS Collaboration.

many cases already the smaller collision systems (proton-proton or proton-lead) start to show comparable signatures at high event multiplicity values. It seems as not so much the size of the colliding ions, but rather the number of final state particles provides for a good parameter to determine or predict the subsequent evolution of, and properties of the system. Recent results on these topics will be discussed in the following sections.

## 2. – Heavy ion results from CMS

For any perturbative calculations using collinear factorization, and also for comparisons to elementary collisions, the thorough knowledge of the gluon distribution functions in nuclei is essential. Parton distribution functions in nuclei are often expressed as nuclear modifications, *i.e.* the ratio $R$ of parton distribution functions in the nucleus and in the proton. $R$ depends on the momentum fraction of the partons, Bjorken-x, and the momentum transfer $Q^2$, and is typically smaller than unity at low $x$ values due to parton shadowing. That is followed by an anti-shadowing region around $x \approx 0.1$, where $R > 1$, then this ratio declines again for $x > 0.3$, which is called the EMC effect. Today there exists only a very limited amount of data that constrains $R$, mainly from deep inelastic scattering and Drell-Yan data, and pion distributions measured at RHIC in deuteron-gold collisions. Systematic uncertainties and differences between various nPDF parametrizations (like nCTEQ15, EPS09, DSSZ, HKN07) often reach a level of 50–100%. There are also different interpretations of the same deuteron-gold data; EPS09 and nCTEQ15 introduce gluon shadowing and anti-shadowing, while DSSZ employs modified parton-to-pion fragmentation while no or minimal modification of the PDF occurs. In this situation, it is mandatory to look for ways to improve the experimental precision.

Measurements of the $J/\psi$ production cross section (which is sensitive to the gluon density in the nucleus) in ultra-peripheral lead-lead collisions at 2.76 TeV have shown that there is a large suppression of the gluon distribution function at $x \approx 8 \times 10^{-3}$ and $Q^2 \approx 2.4\,\mathrm{GeV}^2$ [1]. At high momentum transfers, at $Q^2 \approx 20000\,\mathrm{GeV}^2$, the distribution of the average pseudorapidity ($\eta$) value of dijet pairs was measured in proton-lead and proton-proton collisions, and was shown to be inconsistent with DSSZ and consistent with EPS09, also providing an evidence for gluon anti-shadowing and modification in the EMC region [2].

Another interesting aspect of heavy ion physics are final state anisotropies. It is known that the event-by-event fluctuation of the initial state geometry translates into these final state anisotropies in the distributions of the azimuthal angle ($\phi$) of final state particles, described by the $v_n$ Fourier coefficients. Fluctuations of $v_2$ allows for the extraction of initial anisotropy and the response coefficient thus sheds more light on the mechanism connecting the initial and final state. On fig. 1 the event-by-event distribution of $v_2$ is shown in lead-lead collisions at 5 TeV, for mid-peripheral events. It turns out that the elliptic power function provides a very satisfactory description of the data, from which the indicated set of parameters can be extracted [3].

Higher order Fourier coefficients were also measured, and it was shown that a significant fraction of $v_7$ is coming from non-linear contributions of lower order harmonics [4].

The correlation between various coefficients can be measured using symmetric cumulants, $SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$, shown in fig. 2 in a normalized form. There is a negative correlation between $v_2$ and $v_3$: elliptical events tend not to be very triangular, and vice versa. Surprisingly, plotting the correlation as a function of event multiplicity, the proton-lead and lead-lead collisions produce precisely the same amount of negative

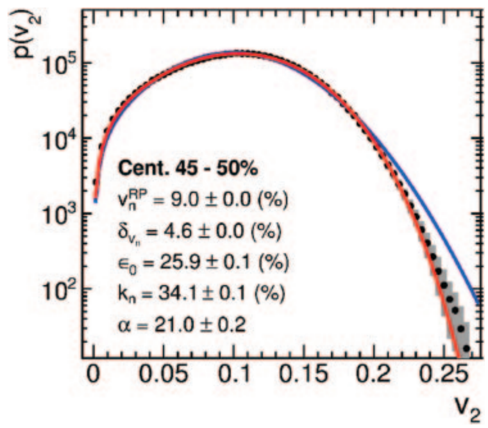


Fig. 1. – Elliptic power law and Bessel-Gaussian parametrizations are fitted to unfolded $v_2$ distributions in mid-peripheral lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$ [3].

correlation, which may well point to a common origin of the observed anisotropy [5].

On the other hand, there is a positive correlation between the elliptical ($v_2$) and rectangular ($v_4$) components of the final state azimuthal distributions, as can be seen on the right panel of fig. 2. In this case however, there is a clear ordering of the correlation as a function of system size, decreasing as a function of the volume of the collision zone, even at the same event multiplicity. This may indicate that different transport properties and mechanisms are at play in small and large collision systems.

Non-central heavy ion collisions create a large magnetic field due to the moving charges in opposite directions; however in proton-lead collisions one expects a much smaller

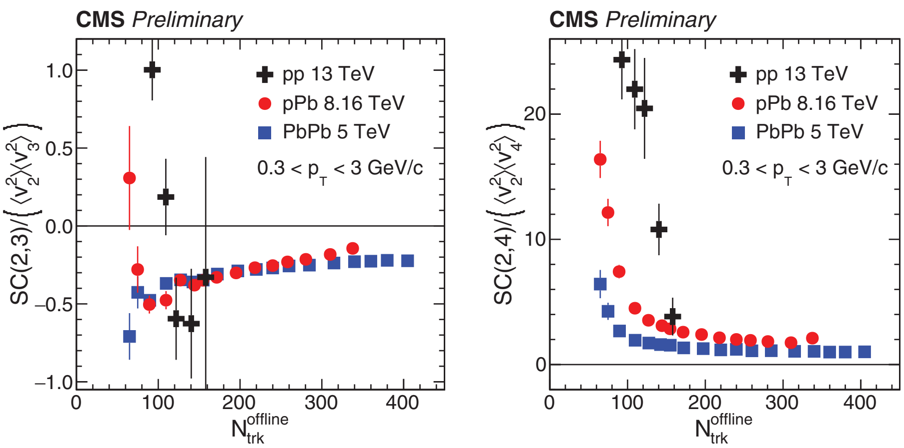


Fig. 2. – The symmetric cumulant for the second and third harmonic (left) and the second and fourth harmonic (right) normalized by $\langle v_2^2\rangle\langle v_3^2\rangle$ and $\langle v_2^2\rangle\langle v_4^2\rangle$ from dihadron correlations, respectively. The $p_T$ range for the considered tracks is $0.3 < p_T < 3\,\mathrm{GeV}/c$ and the results are shown as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, proton-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ and lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ [5].

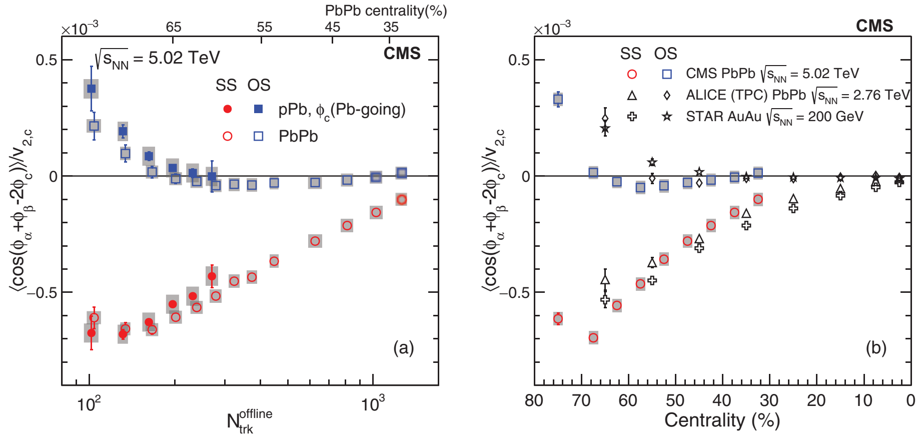


Fig. 3. – The same-sign (SS) and opposite-sign (OS) three-particle correlator averaged over $\eta_\alpha - \eta_\beta < 1.6$ as a function of $N_{\rm trk}^{\rm offline}$ in proton-lead and lead-lead collisions at $\sqrt{s_{\rm NN}} = 5.02\,{\rm TeV}$ are shown. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively [6].

magnetic field than in lead-lead collisions at the same multiplicity value, due to the size of the colliding system. There is almost no correlation between the event plane (the plane containing the centers of the nuclei and their velocity vectors) and the direction of the magnetic field in proton-lead collisions, while there is a very strong correlation in peripheral lead-lead collisions, as one can immediately see from the spatial distribution of the nucleons in the collision zone.

For these reasons, one expects a much smaller charge separation signal, $\gamma = \langle\cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle/v_{2,c}$, in proton-lead collisions. Surprisingly, this is just the opposite from the experimental data, shown on fig. 3, where the opposite- and same-sign three-particle correlator is plotted as a function of multiplicity for the two collision systems. At the same multiplicity, the correlators for proton-lead and lead-lead collisions agree [6]. On the right panel of fig. 3, the lead-lead data is also compared to measurements by other experiments, as a function of centrality (expressed as the percentage of the cross section). These results pose a significant challenge for the chiral magnetic effect interpretation.

It has also been shown that the the asymmetry between the $v_2$ anisotropy coefficients measured for negative and positive particles is a linear function of the charge asymmetry, $A_{\rm ch}$, in the event. The slope of this linear function is not zero in lead-lead collisions, but it was found that it is also very significantly non-zero in proton-lead collisions [7]. This finding also challenges the color magnetic wave interpretation of the heavy ion data.

With the high statistics dataset taken at 5 TeV center of mass energy per nucleon pair, it has also been possible to increase the precision of the measurement of the nuclear modification factor of charged hadrons, which is defined as the ratio of transverse momentum distribution of charged particles in heavy ion collisions and proton-proton collisions normalized by the average number of binary nucleon-nucleon interactions, in lead-lead collisions. While for proton-lead collisions this $R_{\rm AA}$ was measured to increase slightly beyond unity at high $p_T$, due to possible anti-shadowing and/or hadronization effects, $R_{\rm AA}$ in lead-lead collisions around a transverse momentum of 5–10 GeV is heavily suppressed (by an order of magnitude in central collisions), indicating an intensive parton energy loss mechanism in the quark-gluon matter.

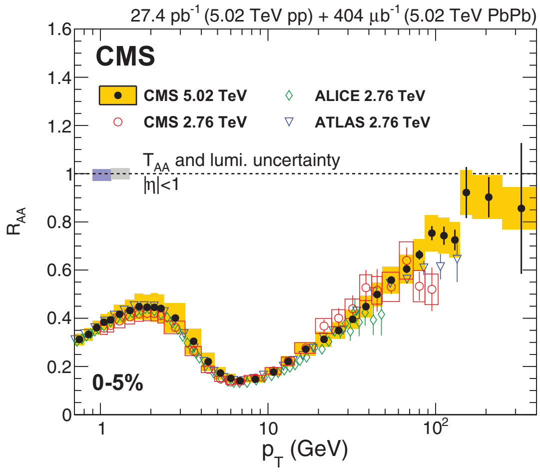


Fig. 4. – Charged-particle nuclear modification factors ($R_{\mathrm{AA}}$) measured for the most central 5% of the lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ compared to results at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ from CMS, ALICE and ATLAS. The yellow boxes represent the systematic uncertainty of the 5.02 TeV CMS points [8].

The $R_{\mathrm{AA}}$ for charged hadrons was measured now up to as much as 400 GeV transverse momentum for the first time. Above 10 GeV the apparent magnitude of the suppression decreases, while at the highest measured transverse momenta $R_{\mathrm{AA}}$ almost reaches unity, as can be seen on fig. 4 for the most central lead-lead collisions at 5 TeV. A very similar suppression was found at 2.76 TeV as well, indicating no or very little dependence on the center of mass energy of the collision. The same quantity measured by the other experiments is also plotted on fig. 4 for comparison, and the consistency was found to be excellent between those [8].

In comparison with the $R_{\mathrm{AA}}$ results measured by CMS for $D^0$ and $B^+$ particles, one can conclude that the suppression values are very similar between these particles within experimental uncertainties, and thus no flavor dependence is visible in nuclear modification factors [9, 10].

A further study on b-jets has also led to similar conclusions: the transverse momentum asymmetry between b-jet pairs and inclusive dijet pairs was not significantly different, thus b-dijets are not more symmetric than dijets at high transverse momenta, in spite of the expectation based on the dead-cone effect, that they are supposed to lose less energy in the high density QCD medium. However, reconstructed b-quark decays into $J/\psi$ mesons in the $p_T < 10\,\mathrm{GeV}$ region show significantly less suppression than charged hadrons do, thus this is the first example where a flavor dependence of energy loss is demonstrated [11].

Related to the previous results, it is also very important to investigate azimuthal asymmetries of final state particles that contain heavy quarks, since these asymmetries can be a result of collective motion at low transverse momenta, and energy loss at high transverse momenta. The second ($v_2$) and third ($v_3$) Fourier coefficients of the azimuthal angle distribution of $D^0$ mesons was measured by the CMS experiment as a function of transverse momentum. Compared to charged particles, the measured $v_2$ and $v_3$ for

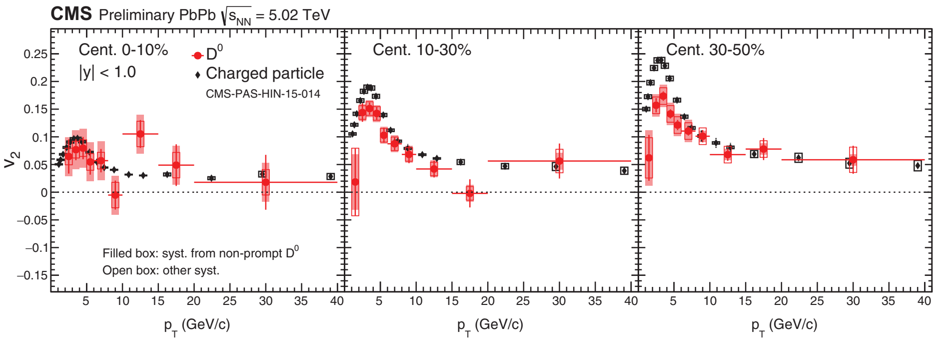


Fig. 5. – Prompt $D^0$ $v_2$ for centrality 0–10% (left), 10–30% (middle) and 30–50% (right) [12]. Charged particle $v_2$ in the same centrality class is also plotted for comparison.

$D^0$ mesons are significantly smaller than those of inclusive charged hadrons, while above 5 GeV the two are consistent with each other. The measured $v_2$ coefficients for $D^0$ mesons [12] in three different centrality regions in lead-lead collisions at $\sqrt{s_{\rm NN}} = 5.02\,{\rm TeV}$ are shown on fig. 5, compared to charged hadrons.

One can thus conclude that at high transverse momenta, the same parton energy loss picture is supported by the nuclear modification factor and by the azimuthal asymmetry measurements for $D^0$ mesons.

The ultimate calibrated measurement of jet energy loss in the high density QCD matter is based on boson-jet pairs, where either a $\gamma$ photon or a $Z$ vector boson is the back-to-back partner of the energetic jet in the heavy ion collision. Since these bosons do not participate in the strong interaction (and Compton scattering is not significant), they will carry the same transverse momentum as the parton that fragments into a jet (at least on tree level). Therefore, $\gamma$-jet or $Z$-jet correlations are direct ways to study the absolute magnitude of jet energy loss.

The CMS Collaboration has measured the distribution of the transverse momentum asymmetry between photons and their jet partners, $x_{J\gamma} = p_T^{\rm Jet}/p_T^{\gamma}$, in lead-lead collisions at $\sqrt{s_{\rm NN}} = 5.02\,{\rm TeV}$ with high statistics. The result can be seen on fig. 6 in four

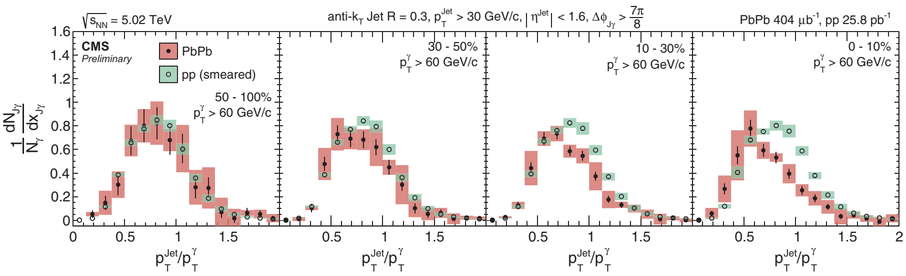


Fig. 6. – Distribution of $x_{J\gamma}$ of photon+jet pairs of proton-proton and lead-lead collisions normalized by the number of photon+jet pairs. The momenta of jets in proton-proton collisions are smeared by the relative jet energy resolution to be used as the reference of each centrality bin. The lines through the points represent the statistical uncertainty while the shaded boxes represent the systematic uncertainty [13].

different centrality regions, compared to the proton-proton reference distribution. In peripheral lead-lead collisions the photon and the jet are as symmetric as they would be expected in proton-proton collisions (left), but in head-on collisions they differ very significantly [13].

The first evidence of $Z$-jet momentum imbalance is also already a public result from the CMS Collaboration, and it is consistent with the higher-precision $\gamma$-jet imbalance in central collisions [14].

While jet energy loss is apparent from these studies, the way energy is rearranged from the jet to somewhere else is not clear from these measurements. For that, jet-hadron correlations are studied in proton-proton and lead-lead collisions at 5 TeV. The two most common observables are evaluated by the CMS Collaboration: the jet shapes (related to angular distribution of the jet components) and jet fragmentation functions (related to the momentum distribution of jet components). These are sensitive to the possible medium response to hard probes and induced radiation. For example, jet shape results show that there is an excess of charged particles at large radii (distance from the jet axis) in central lead-lead collisions compared to proton-proton collisions. The "lost" energy from the jets is redistributed at larger angular distances with respect to the jet axis [15].

Jet sub-structure studies can also reveal whether the jet suppression correlates with the shower shape. This would be the case if the partons within a jet are separated enough so that they are seen separately by the colored medium, or in case of modification of parton branching in the medium, or if there are correlated background particles with the shower in the medium. These measurements have shown that jets with two hard sub-jets are relatively more suppressed than jets with a single core [16].

Finally, the temperature of the hot QCD medium can be probed by measurements of quarkonium states, as it is already known that the production of these is suppressed with respect to proton-proton collisions, and the suppression increases with the size of the quarkonium state (with decreasing binding energy). The first measurement of $\Upsilon$ suppres-

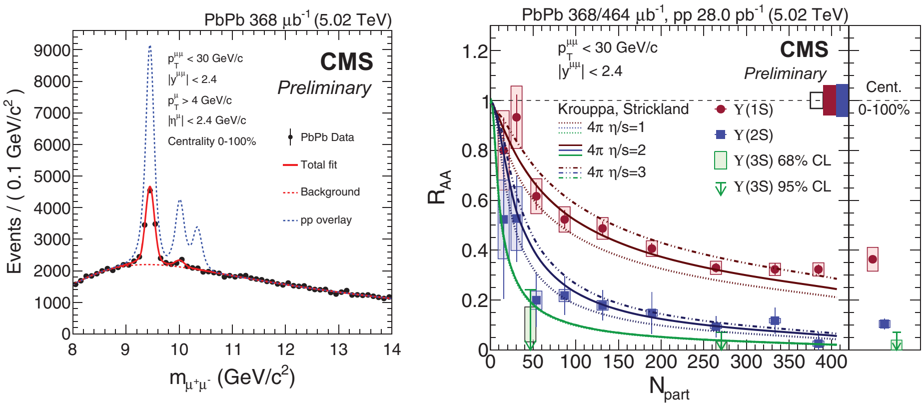


Fig. 7. – Left: invariant mass distribution of muon pairs in proton-proton (left) and lead-lead (right) collisions, for the kinematic range $p_T^{\mu\mu} < 2\,\mathrm{GeV}/c$ and $|y^{\mu\mu}| < 2.4$. Right: nuclear modification factors of $\Upsilon$(1S), $\Upsilon$(2S) and $\Upsilon$(3S) mesons as a function of the number of nucleons that participate in the collision, $N_{\mathrm{part}}$. The error bars represent the statistical and the boxes the systematic uncertainties.

sion in the high-statistics lead-lead dataset at 5 TeV confirmed the very large suppression of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states, with $\Upsilon(3S)$ being the most suppressed, as can be seen in fig. 7. Thus, the sequential suppression pattern is still very significant in the new data, which has the highest precision ever achieved in this topic. However, the $\Upsilon(3S)$ state is so much suppressed that the $\Upsilon(3S)$ production is still not significantly visible in lead-lead collisions, even in this dataset [17]. There is an indication that the suppression of these states are larger at 5.02 TeV compared to 2.76 TeV, which is consistent with predictions, given that the medium is hotter and denser at 5.02 TeV.

## 3. – Summary

In summary, the CMS Collaboration has conducted an extremely successful low-pileup proton-proton and lead-lead data taking period in 2015, and an equally fruitful proton-lead run in 2016, with integrated luminosity exceeding expectations by far. The new data revealed an evidence of gluon shadowing and anti-shadowing, and EMC effect in the lead nucleus. A remarkable similarity was found between the collective phenomena observed in small and large collision systems. The charge separation signal measured in proton-lead collisions challenges the pure chiral magnetic effect and chiral magnetic wave interpretation of the heavy ion data. High-precision measurements were completed using boson-jet correlations to evaluate the absolute jet energy loss in the medium, which does not appear to be flavor-dependent except at low transverse momenta, but depends on the shower shape. And finally, the sequential suppression of quarkonium states was reconfirmed in the most energetic microscopic collisions ever achieved in a laboratory.

* * *

The author wishes to thank for their support the Hungarian Academy of Sciences “Lendület” (Momentum) Program (LP 2015-7/2015) and the National Research, Development and Innovation Office of Hungary (K 124845 and FK_17 123842).

REFERENCES

[1] CMS Collaboration, *Phys. Lett. B*, **772** (2017) 489.
[2] CMS Collaboration, *Eur. Phys. J. C*, **74** (2014) 2951, CMS-PAS-HIN-16-003.
[3] CMS Collaboration, CMS-PAS-HIN-16-019.
[4] CMS Collaboration, CMS-PAS-HIN-16-018.
[5] CMS Collaboration, CMS-PAS-HIN-16-022, arXiv:1709.09189.
[6] CMS Collaboration, *Phys. Rev. Lett.*, **118** (2017) 122301.
[7] CMS Collaboration, CMS-PAS-HIN-16-017, arXiv:1708.08901.
[8] CMS Collaboration, *JHEP*, **04** (2017) 039.
[9] CMS Collaboration, CMS-PAS-HIN-16-001, arXiv:1708.04962.
[10] CMS Collaboration, *Phys. Rev. Lett.*, **119** (2017) 152301.
[11] CMS Collaboration, *Eur. Phys. J. C*, **77** (2017) 252.
[12] CMS Collaboration, CMS-PAS-HIN-16-007, arXiv:1708.03497.
[13] CMS Collaboration, CMS-PAS-HIN-16-002.
[14] CMS Collaboration, *Phys. Rev. Lett.*, **119** (2017) 082301.
[15] CMS Collaboration, CMS-PAS-HIN-16-020.
[16] CMS Collaboration, CMS-PAS-HIN-16-006, arXiv:1708.09429.
[17] CMS Collaboration, CMS-PAS-HIN-16-023.