Low-mass dimuon measurements in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC

Antonio Uras
IPNL, Université Claude Bernard Lyon-I and CNRS-IN2P3, Villeurbanne, France
E-mail: antonio.uras@cern.ch

Abstract.
Low-mass dimuon production, including light vector mesons $\rho$, $\omega$, $\phi$, provides key information on the hot and dense state of strongly interacting matter produced in high-energy heavy-ion collisions. In particular, strangeness production can be studied via $\phi$ meson measurements, while the detailed description of the full dimuon mass spectrum down to the kinematic threshold can be used to reveal in-medium modifications of hadron properties and the thermal emission arising from the medium. Measurements in pp and p-A systems, in absence of hot nuclear matter effects, must be used as a reference to test our knowledge of the processes expected to contribute to dilepton production. Dimuon production is studied with the ALICE apparatus at the LHC at forward rapidity ($2.5 < y < 4$) with the Muon Spectrometer. In this contribution, results on low-mass dimuon production are shown, for various center-of-mass energies per nucleon pair, in pp, p-Pb, and Pb-Pb collisions.

1. Introduction
Low-mass dimuon production at the LHC energies is dominated by the 2-body and Dalitz decays of the light neutral mesons $\eta, \rho, \omega, \eta'$ and $\phi$ — the so-called “hadronic cocktail” — with dimuons from open charm and open beauty decay processes contributing to the invariant mass continuum. An increased production cross section for the open charm and open beauty processes, relative to the hadronic cocktail, marks the main evolution with respect to the low-mass dilepton measurements at the SPS [1] and RHIC [2, 3] energies.

Describing the observed low-mass dimuon production in pp collisions allows for the study of particle production mechanisms in elementary hadronic interactions in the light quark sector, while observations in p-A collisions are sensitive to initial state effects affecting particle production in cold nuclear matter. In heavy-ion collisions, dimuons deploy their full potential as penetrating probes: insensitive to the strong color field dominating inside the QCD matter, leptons arrive to the detectors almost unaffected, providing an ideal tool to probe the whole evolution of the system. Low-mass dimuon measurements in heavy-ion collisions, in particular, allow the identification of hot nuclear matter effects related to the creation of an extended volume of quark-gluon plasma (QGP), to its hydrodynamical evolution, and to the chiral symmetry restoration expected to occur within the deconfined system. In this case, key-observables are strangeness production via $\phi$ meson measurement, the spectral function modification of the short-lived $\rho$ meson, and the observation of direct thermal radiation from the QGP phase. The possibility to observe the $\eta$ meson via its prominent Dalitz decay as well as the $\omega$ meson via its 2-body decay completes the rich spectrum of information which can be accessed by the analysis
of the low-mass dimuon spectrum. In this contribution, the main results from the available ALICE low-mass dimuon measurements performed during the LHC Run 1 in pp, p-Pb and Pb-Pb collisions are reviewed.

The ALICE experiment at the CERN LHC measures low-mass dimuon production at forward rapidity, complementing the low-mass dielectron observations performed at mid-rapidity. Identification and measurement of muons are performed in the Muon Spectrometer [4], covering the pseudo-rapidity region $2.5 < \eta_{lab} < 4$. Starting from the interaction point (IP), the Muon Spectrometer is composed of the following elements: a hadron absorber which filters out hadrons; a 3 T·m integrated field dipole magnet; a set of five tracking stations, each one composed of two cathode pad chambers with a spatial resolution of about 100 \( \mu \)m in the bending direction; an iron wall, which absorbs the residual secondary hadrons emerging from the absorber; the muon trigger system, consisting of four planes of resistive plate chambers with a time resolution of about 2 ns. Uncorrelated muon pairs coming from semi-muonic decays of \( \pi \) and \( K \) mesons represent the main background source affecting measurements in the dimuon channel, especially at low invariant masses. In all the measurements presented in the following, the combinatorial background is evaluated using an event mixing technique [5] and subtracted from the raw dimuon invariant mass spectrum.

2. Results in pp Collisions
Low-mass dimuon production in pp collisions were measured by ALICE at \( \sqrt{s} = 2.76 \) and 7 TeV [6, 5]. These results allowed to exclude, for the first time in elementary hadronic reactions at the LHC energies, any significant contribution to the low-mass dimuon spectrum beyond the already cited hadronic cocktail and the open charm and open beauty processes, see left panel of Figure 1. The \( \phi \) signal could be extracted and the differential cross-sections was measured as a function the transverse momentum (\( p_T \)) for \( 1 < p_T < 5 \) GeV/c (see right panel of Figure 1) and compared to the predictions from PHOJET [7] and the ATLAS-CSC, D6T [8], the Perugia0 and Perugia11 [9] tunes of PYTHIA [10]. At both energies, an overall good agreement is found between predictions and data, with the exception of the Perugia0 and Perugia11 tunes of PYTHIA which underestimate the measured cross section by a factor between 1.5 and 2. The integrated cross section over the accessible \( p_T \) range \( 1 < p_T < 5 \) GeV/c and \( 2.5 < y < 4 \) was measured to be \( \sigma_\phi = 0.940 \pm 0.055 \) (stat.) \( \pm 0.044 \) (syst.) mb and \( \sigma_\phi = 0.566 \pm 0.084 \) (stat.) \( \pm 0.076 \) (syst.) mb at \( \sqrt{s} = 2.76 \) and 7 TeV, respectively.

3. Results in p-Pb Collisions
Data in p-Pb collisions were taken by ALICE at \( \sqrt{s_{NN}} = 5.02 \) TeV [6], with the Muon Arm accessing two different rapidity regions\(^1\): \( 2.03 < y < 3.53 \) (p-going) and \(-4.46 \leq y \leq -2.96 \) (Pb-going). In the following, these two rapidity ranges will be referred to as “forward” and “backward”, respectively.

The analysis of the p-Pb data shares the same strategy of the pp data: after subtraction of the combinatorial background, estimated by means of an event mixing technique, the invariant mass spectrum of the signal was described in terms of the expected sources. The analysis focused on the \( \phi \) meson measurement: the \( \phi \) cross section, integrated over the accessible \( p_T \) range, \( 1 < p_T < 7 \) GeV/c, is shown as a function of rapidity in the left panel of Figure 2, exhibiting a significant asymmetry between the forward and backward rapidity regions. The comparison between the data and the predictions by HIJING [11] and DPMJET [12] clearly shows how the models — which successfully described charged particle production at mid-rapidity in the same collision system [13] — fail to properly reproduce the shape and the normalisation of the observed rapidity dependence of the \( \phi \) cross section. Still, HIJING prediction qualitatively

\(^1\) The sign of \( y_{cms} \) is defined by assuming the proton beam to have positive rapidity.
reproduces the forward-backward asymmetry observed in the data, as well as — ignoring the normalisation — the shape of the $y$-dependence in the backward region. DPMJET, on the contrary, fails to reproduce even qualitatively the observed forward-backward asymmetry. Averaging over the available $p_T$ range, the discrepancy between the data and the predictions from HIJING and DPMJET amounts to $\sim 18\%$ and $\sim 57\%$, respectively, at backward rapidity and $\sim 5\%$ and $\sim 9.5\%$, respectively, at forward rapidity.

The $\phi$ meson nuclear modification factor $R_{pPb}$ is defined as the ratio between the production cross section $\sigma_{pPb}(p_T)$ in p-Pb collisions and the cross section $\sigma_{pp}(p_T)$ in pp collisions evaluated at $\sqrt{s} = 5.02$ TeV, scaled by $A_{Pb}$: $R_{pPb}(p_T) = \sigma_{pPb}(p_T)/\left(\sigma_{pp}(p_T) \cdot A_{Pb}\right)$, where $A_{Pb}$ is the nuclear mass number for the Pb nucleus. Since for the pp cross section $\sigma_{pp}$ at $\sqrt{s} = 5.02$ TeV no direct measurement is currently available, it was evaluated by interpolating the already cited measurements in the rapidity interval $2.5 < y < 4$ at $\sqrt{s} = 2.76$ and 7 TeV. The nuclear modification factor $R_{pPb}$ as a function of $p_T$ is shown in the center and right panels of Figure 2 for the backward and forward rapidity regions. In the p-going direction a rising trend of $R_{pPb}$ is observed from $\sim 0.5$ to $\sim 1$, when going from $p_T = 1$ GeV/$c$ to $p_T = 4$ GeV/$c$. This observation is compatible with the behaviour of charged particles at forward rapidity at RHIC energies [14, 15], and at mid-rapidity at LHC energies [16]. In the Pb-going direction, on the other hand, an enhancement is observed for $R_{pPb}$, reaching values as large as $\sim 1.6$ around $p_T = 3-4$ GeV/$c$. In both rapidity regions, observations are found to be in agreement with a recent measurement of $\phi$ meson production at the RHIC [17]. An interpretation of these results, either in terms of an initial-state (Cronin-like) effect or a final-state effect related to radial flow in p-Pb, is not possible yet, due to a general lack of theoretical predictions for soft particle production at forward rapidity in p-A collisions at the LHC energies.

4. Results in Pb-Pb Collisions
ALICE collected data in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Due to the hardware trigger threshold at $p_T \sim 1$ GeV/$c$ for the single muons involved in this data taking, the acceptance for low-mass dimuons is negligible below $p_T = 2$ GeV/$c$. As for the pp and p-Pb analyses, the low-mass dimuon spectrum is described, after subtraction of the combinatorial background, in terms of the superposition of the hadronic cocktail and the open charm and open beauty.

Figure 1. Left: Fit to the low-mass dimuon spectrum in pp collisions at $\sqrt{s} = 2.76$ TeV; cyan boxes: systematic uncertainty from background subtraction; red band: uncertainty in the relative normalization of the sources. Right: $\phi$ cross section as a function of $p_T$ compared with predictions from PHOJET and several tunes of PYTHIA.
decay processes. In this way, the signal for the $(\rho + \omega)$ and $\phi$ mesons could be extracted in the $p_T$ interval $2 < p_T < 5$ GeV/c and for $2.5 < y < 4$. The signal-over-background ratio at the $\phi$ peak ranges from $\sim 0.1$ for the most central collisions (0-20% centrality), to $\sim 3$ for peripheral collisions (60-90% centrality). Strangeness enhancement in Pb-Pb collisions could thus be studied considering the evolution of the $\phi/(\rho + \omega)$ ratio as a function of the centrality. This ratio, shown as $BR_{\phi \rightarrow 2\mu}\sigma_{\phi}/(BR_{\rho \rightarrow 2\mu}\sigma_{\rho} + BR_{\omega \rightarrow 2\mu}\sigma_{\omega})$, is plotted in the left panel of Figure 3. The centrality of the collision is expressed in terms of the number of participant nucleons $N_{\text{part}}$ — i.e. the number of nucleons that undergo at least one inelastic collision with another nucleon. The pp value ($N_{\text{part}} = 2$) is also shown. The ratio increases from pp to Pb-Pb and tends to saturate already in semi-peripheral collisions in the 40-60% centrality class. The value for 0-20% most central Pb-Pb collisions is about two times the one measured in pp collisions. It should be noted that, due to the limited $p_T$ range accessible and the different masses of the considered particles, this measurement may also be sensitive to the radial flow mechanism, preventing firm conclusions to be established in terms of genuine strangeness enhancement.

The nuclear modification factor for the $\phi$ meson is defined as $R_{AA} = \langle\phi\rangle/(\sigma_{pp}(T_{AA}))$, where $\langle\phi\rangle$ is the $\phi$ yield in a given kinematic range, $\sigma_{pp}$ is the $\phi$-production cross section in pp collisions in the same kinematic range, and $T_{AA}$ is the average nuclear overlap function of the considered centrality class. The $R_{AA}$ was extracted for the $\phi$ meson as a function of the centrality, using as a reference the pp results obtained at the same nucleon-nucleon center-of-mass energy as for the Pb-Pb collisions. The centrality dependence of $R_{AA}(\phi)$, again expressed as a function of $N_{\text{part}}$, is shown in the right panel of Figure 3. In the figure, the results from the $\phi$ measurement at mid-rapidity in the $KK$ channel [18], in the same $p_T$ range as the dimuon channel, are also reported. The comparison between the two channels suggests a systematic difference between the centrality dependence of the $R_{AA}$ measured at mid and forward rapidities, related to a different centrality dependence of the $\phi$ yield per participating nucleon in the two rapidity ranges (not shown in this contribution). Further investigations are currently ongoing on this point, unfortunately limited by the narrow $p_T$ range accessible with the dimuon channel.

References

[1] Uras A (NA60 Collaboration) 2012 Acta Phys. Polon. Supp. 5 465–470 (Preprint 1201.0270)
[2] Adamczyk L et al. (STAR Collaboration) 2012 Phys. Rev. C86 024906 (Preprint 1204.1890)
[3] Tserruya I (PHENIX Collaboration) 2013 Nucl. Phys. A904-905 225c–232c (Preprint 1211.6002)
[4] Aamodt K et al. (ALICE Collaboration) 2008 JINST 3 S08002
[5] Abelev B et al. (ALICE Collaboration) 2012 Phys. Lett. B710 557–568 (Preprint 1112.2222)
[6] Adam J et al. (ALICE Collaboration) 2015 (Preprint 1506.09206)
[7] Engel R and Ranft J 1996 Phys. Rev. D54 4244–4262 (Preprint hep-ph/9509373)
Figure 3. Left: ratio $BR_{\phi \to \mu\mu}\sigma_{\phi}/(BR_{\rho \to \mu\mu}\sigma_{\rho} + BR_{\omega \to \mu\mu}\sigma_{\omega})$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, as a function of $N_{\text{part}}$. Right panel: nuclear modification factor $R_{AA}$ for the $\phi$ meson, as a function of $N_{\text{part}}$; forward rapidity measurement in the $\mu\mu$ channel is compared with the mid-rapidity one in the $KK$ channel.

[8] Field R 2008 Acta Phys.Polon. B39 2611–2672
[9] Skands P Z 2010 Phys. Rev. D82 074018 (Preprint 1005.3457)
[10] Sjostrand T, Mrenna S and Skands P Z 2006 JHEP 0605 026 (Preprint hep-ph/0603175)
[11] Wang X N and Gyulassy M 1991 Phys. Rev. D44 3501–3516
[12] Roesler S, Engel R and Ranft J 2000 1033–1038 (Preprint hep-ph/0012252)
[13] Abelev B et al. (ALICE Collaboration) 2013 Phys. Rev. Lett. 110 032301 (Preprint 1210.3615)
[14] Arsene I et al. (BRAHMS Collaboration) 2004 Phys. Rev. Lett. 93 242303 (Preprint nucl-ex/0403005)
[15] Back B et al. (PHOBOS Collaboration) 2004 Phys. Rev. Lett. 93 082301 (Preprint nucl-ex/0311009)
[16] Abelev B et al. (ALICE Collaboration) 2013 Phys. Rev. Lett. 110 082302 (Preprint 1210.4520)
[17] Adare A et al. (PHENIX Collaboration) 2015 (Preprint 1506.08181)
[18] Abelev B B et al. (ALICE Collaboration) 2014 (Preprint 1404.0495)