Recent results on soft probes of the Quark-Gluon Plasma from the ATLAS experiment at the LHC

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Abstract

Measurements of low-\(p_T\) particle production have provided valuable insight on the production and evolution of the quark-gluon plasma in Pb+Pb collisions at the LHC. In particular, measurements of collective flows and their anisotropies directly probe the strongly-coupled dynamics of the quark-gluon plasma and test hydrodynamic model descriptions of its evolution. We present recent results from a variety of single and multi-particle measurements in lead-lead and proton-lead collisions with the ATLAS detector that probe the collective dynamics of the quark-gluon plasma and possibly provide evidence for collectivity even in small systems.

Keywords: quark-gluon plasma, collective flow, heavy ion collisions, proton-ion collisions

1. Introduction

The Quark-Gluon Plasma (QGP) has been first observed in experiments at RHIC [1, 2, 3] and since then it has been intensively studied in relativistic heavy ion collision experiments. Significantly higher collision energies available at the LHC compared to RHIC, result in increased volume, lifetime and temperature of QGP. Even at these high energies, still more than 99% of produced particles have momenta below 2 GeV/c and therefore the study of these ‘soft’ particles and the physical processes involved in their production are of major interest for the comprehension of the QGP properties.

In this short review we present recent measurements performed with the ATLAS detector [4] and related to the investigation of the QGP properties with help of ‘soft probes’. The measurements are based on 7 \(\mu b^{-1}\) of Pb+Pb collision data at \(\sqrt{s_{NN}} = 2.76\) TeV recorded in 2010 and 28 nb\(^{-1}\) of p+Pb collision data at \(\sqrt{s_{NN}} = 5.02\) TeV recorded in 2013.

A proxy to the QGP volume produced in a collision is the collision centrality. In ATLAS centrality of events is determined with the use of sum of transverse energy deposited in the forward calorimeter (FCal) covering the pseudorapidity range 3.2 < |\(\eta\)| < 4.8. In case of Pb+Pb collisions the sum on both sides and in case of p+Pb collisions the sum on the Pb-going side only are taken into account [5, 6]. The centrality intervals are expressed in percentiles of the total inelastic non-Coulomb Pb+Pb or p+Pb cross sections, respectively. For the correlation between centrality interval and the average number of participants the Glauber model is used for Pb+Pb collisions and both the Glauber and Glauber-Gribov colour fluctuation [7] models for p+Pb collisions.

One of the most extensively studied quantities in heavy-ion collisions is the anisotropy in the azimuthal angle distribution of emitted particles. The final state anisotropy arises from the initial spatial asymmetry of the overlap zone in the collision of two nuclei with non-zero impact parameter. The final state momentum anisotropy is usually characterized by the coefficients \(v_n\) of the Fourier decomposition of the azimuthal angle distribution of emitted particles:

\[
E \frac{d^3N}{dp_T d\phi dy} = \frac{1}{p_T} \frac{d^3N}{d\phi d\eta} = \frac{1}{2\pi p_T} \frac{E}{d\eta} \frac{d^2N}{dp_T d\eta} \times
\]
\[
\times \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)\right)
\]  

(1)

where \(\Phi_n\) is the azimuthal angle of the \(n\)-th order symmetry plane of the initial geometry and \(v_n \equiv \langle e^{i n(\phi - \Phi_n)} \rangle = \langle \cos n(\phi - \Phi_n) \rangle\) is the magnitude of the \(n\)-th flow harmonics.

2. Flow harmonics with multiparticle cumulants

Several methods exist to extract \(v_n\) coefficients from data. In [8] ATLAS has recently provided new measurements of \(v_n\) for \(n = 1 \sim 4\) with the Fourier coefficients evaluated using multi-particle cumulants calculated with the generating function method [9, 10]. 2k-particle correlations are defined as:

\[
\langle cor_{2k}\rangle = \langle e^{i n(\phi_i + \phi_{i+1} + \phi_{i+2})} \rangle = \langle v_n(2k)^{2k} \rangle
\]  

(2)

where the notation \(v_n(2k)\) is used for the \(v_n\) flow harmonic derived from the 2k-particle correlations, and \(k\) is an integer. Azimuthal angles of particles forming a 2k-particle cluster are denoted by \(\phi_i\), where \(l = 1, \ldots, 2k\). The double angled brackets denote an average, first over charged particles in an event, and then over events, while the single angled brackets denote averaging over events. The multi-particle correlation, \(\langle cor_{2k}\rangle\), includes contributions from the collective anisotropic flow and from non-flow effects. It was proposed in Refs. [9, 10] to exploit the cumulant expansion of multi-particle correlations in order to reduce the non-flow contribution. The anisotropic flow related to the initial geometry is a global, collective effect involving correlations between all outgoing particles. Thus, in the absence of non-flow effects, \(v_n(2k)\) is expected to be independent of \(k\). On the other hand, most of the non-flow correlations, such as resonance decays or interference effects, contribute only to correlations between small numbers of particles. The idea of using 2k-particle cumulants is to suppress the nonflow contribution by eliminating the correlations which act between fewer than 2k particles.

The transverse momentum dependence of the higher order harmonics, \(v_3\) and \(v_4\), is shown in Fig. 1 and compared to the results obtained with the event-plane (EP) method [5]. Due to the large uncertainties on the harmonics measured with four-particle cumulants, especially for events with low multiplicities, the results are shown in wide centrality ranges: for \(v_3\) in the two broad centrality intervals, 0 – 25% and 25 – 60%, and for \(v_4\) in the full accessible centrality range, 0 – 25%. In addition, the results for \(v_n(4)\) are shown in fine \(p_T\) bins at low transverse momenta, up to 4 GeV, while the last \(p_T\) point covers the range from 4 GeV to 20 GeV. Similarly to \(v_2\) (not shown), smaller short-range jet-like correlations are observed in \(v_{3,4}(EP)\) as compared to \(v_{3,4}(2)\). Significantly non-zero values of the third and fourth flow harmonics calculated with four-particle cumulants are observed with a \(p_T\) dependence similar to that of \(v_2\). The \(v_n(4)\) harmonic is systematically smaller than \(v_n(2)\), consistent with the suppressed non-flow effects in flow harmonics obtained with cumulants of more than two particles. It is noted that the difference between \(v_3(4)\) (\(v_3(4)\)) and \(v_3(EP)\) (\(v_3(EP)\)), which amounts to a factor of about two, is much larger than the difference between \(v_2(4)\) and \(v_3(EP)\), which is of the order of 30%. This indicates that fluctuations of higher-order flow harmonics are much stronger than fluctuations of \(v_2\).

The pseudorapidity dependence of \(v_n(2k)\) has been studied as a function of centrality for flow coefficients integrated over the \(p_T\) range from 0.5 GeV to 20 GeV. No strong dependence on pseudorapidity is observed for any of the second flow harmonic measurements in the centrality interval 0 – 25% (left plot) and 25 – 60% (middle plot) [8]. The right plot shows the same results for \(v_4\) for the centrality interval 0 – 25%. Statistical errors are shown as bars and systematic uncertainties as bands. The highest \(p_T\) measurement for \(v_n(4)\) (\(v_n(EP)\)) is integrated over the \(p_T\) range 4 – 20 (8 – 20) GeV.
pendence is observed for $v_3[4]$ as shown in Fig. 2(left) for harmonics averaged over the full accessible centrality range ($0 - 60\%$). The fourth-order flow harmonics, $v_4[4]$, shows no significant dependence on pseudorapidity, within the measurement uncertainties, over the centrality range $0 - 25\%$. A systematic reduction in the non-flow contribution is observed for $v_n[EP]$ as compared to $v_n[2]$.

Also the centrality dependence of the flow harmonics integrated over full range in $\eta$ and $p_T$ and obtained with cumulants of various orders has been studied as a function of $\langle N_{\text{part}} \rangle$. It is interesting to compare flow harmonic measurements obtained with different methods, which have different sensitivities to non-flow correlations and flow harmonic fluctuations. Since the higher-order flow harmonics, $v_n[2k]$ ($n > 2$), are measured with the cumulant method with up to four-particle cumulants, the $v_n[2]$ and $v_n[4]$ are only included in the comparison. Figure 2(right) shows the comparison of $v_3$ obtained using the cumulant method with the ATLAS results obtained with the event-plane method, $v_3[EP]$. The mean values of the measured $p(v_3)$ distributions are also shown and marked as $v_3[EP]$. Over the accessible centrality range, a systematic pattern with $v_n[2] > v_n[EP] > v_n[EP]$ has been observe for $v_n$ for $n = 2, 3, 4$. The $v_n[2]$ values are the largest due to large contributions from short-range two-particle correlations, which are suppressed in the event-plane $v_n$ measurements. The $v_n$ coefficients measured with the event-plane method are systematically larger than the mean values of the event-by-event measurement of flow harmonics. This difference is naturally attributed to the flow fluctuations, which contribute to $v_n[EP]$ but are suppressed in $v_n[EP]$. The flow coefficients measured with the four-particle cumulant method are the smallest, mainly due to the contribution from flow fluctuations, which is negative for $v_n[4]$ and positive for $v_n[EP]$. In addition, some residual two-particle correlations unrelated to the azimuthal asymmetry in the initial geometry contribute to $v_n[EP]$, but are negligibly small in the case of $v_n[4]$.

3. Event plane correlations

The $n^{th}$-order harmonic has a $n$-fold symmetry in azimuth and is thus invariant under the transformation $\Phi_n \rightarrow \Phi_n + 2\pi/n$. Therefore, a general definition of the relative angle between two event planes, $a_n\Phi_n + a_m\Phi_m$, has to be invariant under a phase shift $\Phi_i \rightarrow \Phi_i + 2\pi/l$. It should also be invariant under a global rotation by any angle. The first condition requires $a_n$ ($a_m$) to be multiple of $n$ ($m$), while the second condition requires the sum of the coefficients to vanish: $a_n + a_m = 0$.

The relative angle $\Phi_{n,m} = k(\Phi_n - \Phi_m)$, with $k$ being the least common multiple (LCM) of $n$ and $m$, satisfies these constraints, as does any integer multiple of $\Phi_{n,m}$. The correlation between $\Phi_n$ and $\Phi_m$ is completely described by the differential distribution of the event yield $dN_{\text{expt}}/d(k(\Phi_n - \Phi_m))$. This distribution must be an even function owing to the symmetry of the underlying physics and hence can be expanded into the following Fourier series:

$$\frac{dN_{\text{expt}}}{d(k(\Phi_n - \Phi_m))} \propto 1 + 2 \sum_{j=1}^{\infty} V^j_{n,m} \cos jk(\Phi_n - \Phi_m)$$

where $V^j_{n,m} = \langle \cos jk(\Phi_n - \Phi_m) \rangle$. The measurement of the two-plane correlation is thus equivalent to measuring a set of cosine functions $\langle \cos jk(\Phi_n - \Phi_m) \rangle$ averaged over many events [11]. This discussion can be generalized for correlations involving three or more event planes.

Several two- and three-plane correlators have been recently measured by the Atlas experiment in [12]. Two methods have been used to obtain correlators: the event plane (EP) method and the ‘scalar-product’ (SP) method [13]. The SP method removes potential bias in the EP method arising from the effects of event-by-event fluctuations of the flow and multiplicity and is denoted in the following with the subscript ‘w’. Figure 3 shows an example of two-plane correlator. The results from both EP method and SP method are shown with their respective systematic uncertainties. The magnitude of the correlations from the SP method is always larger than from the EP method. This feature is also present in case of other correlators. The measurements are com-
pared to the Glauber model and to a multi-phase transport (AMPT) model [14]. The AMPT model combines the initial-state geometry fluctuations of the Glauber model and final-state interactions through a parton and hadron transport model. The AMPT model generates collective flow by elastic scatterings in the partonic and hadron transport model. The AMPT model generates events to be analyzed with the same procedures as in the data. Good agreement is observed between the data and the AMPT calculation, and in particular the model predicts correctly the stronger signal observed with the SP method, whereas the Glauber model is not able to describe the data.

4. Integrated elliptic flow

Recently ATLAS experiment has also measured the centrality and pseudorapidity dependence of the elliptic flow integrated over the $p_T$ of charged particles [15]. Different methods for track reconstruction have been used in order to exploit a large range in particle $p_T$:

- the tracklet (TKT) method used for the field-off data in order to reach charged-particle $p_T$ below 0.1 GeV,
- the pixel track (PXT) method used to reconstruct tracks with $p_T \geq 0.1$ GeV using only the pixel detector in the field-on data sample,
- the inner detector track (IDT) method for the field-on data sample, the default ATLAS reconstruction method, for which all ID sub-detectors are used and the track $p_T$ is limited to $p_T \geq 0.5$ GeV.

Figure 4 shows the centrality dependence of $v_2$ integrated over $|\eta| < 1$. For the TKT method, $v_2$ is integrated over $p_T > 0.07$ GeV. For the PXT method, $v_2$ is integrated over $p_{T,0} > p_T < 5$ GeV and $p_{T,0}$ is varied from 0.1 to 0.5 GeV in steps of 0.1 GeV. Also shown is the $v_2$ value obtained from the IDT method integrated over $0.5 < p_T < 5$ GeV. The TKT method with $p_{T,0} = 0.07$ GeV gives results consistent with the $v_2$ values obtained with the PXT method with $p_{T,0} = 0.1$ GeV, as could be expected due to the very low charged-particle density and small $v_2$ signal in the momentum range below 0.1 GeV. This indicates that there is no need to extrapolate the measurements obtained with tracklets down to $p_T = 0$ in order to obtain a reliable estimate of $v_2$ integrated over the whole kinematic range in $p_T$.

Furthermore, for the PXT method such an extrapolation would result in a very small correction to the measured integrated flow, well within the uncertainties of the measurement. This is in contrast to the integrated $v_2$ with $p_{T,0}$ chosen at higher values, as also shown in Fig. 4. It can be seen that the integrated $v_2$ increases almost linearly with $p_{T,0}$ for $p_{T,0} > 0.1$ GeV. Good agreement between the PXT and IDT methods is observed at $p_{T,0} = 0.5$ GeV.

In Fig. 5, the results of the analysis are compared to the integrated $v_2$ measured by CMS [16] with $p_{T,0} = 0.3$ GeV. In this comparison, the sensitivity to $p_{T,0}$ is clearly visible. A systematically larger $v_2$ is observed for the higher value of $p_{T,0}$ as a consequence of the strong increase of $v_2$ with increasing $p_T$. The $\eta$ dependence of the $p_T$-integrated $v_2$ provides useful constraints on the initial conditions of heavy-ion collisions used in model descriptions of the system’s evolution.
5. Correlations between flow harmonics

Preliminary results on correlations between the elliptic flow coefficient, \( v_2 \), and higher-order flow harmonics, \( v_n \), \( n = 3, 4, 5 \) have been measured by the ATLAS experiment [17]. The \( v_2 - v_n \) correlations are measured as a function of centrality, and, for events within the same centrality interval, also as a function of event ellipticity. The ellipticity of the events is characterized with the so-called ‘flow vector’ calculated from the transverse energy (\( E_T \)) deposited in the FCal:

\[
\vec{q}_2 = (q_{x,2}, q_{y,2}) = \frac{1}{\Sigma w_i} (\Sigma [w_i \cos 2 \phi_i], \Sigma [w_i \sin 2 \phi_i]) - \langle \vec{q}_2 \rangle_{\text{evts}}
\]

where the weight \( w_i \) is the \( E_T \) of the \( i \)-th tower in the FCal. Subtraction of the event-averaged centroid, \( \langle \vec{q}_2 \rangle_{\text{evts}} \), removes biases due to detector effects. The angle \( \Psi_2 = \frac{1}{2} \arctan (q_{y,2}/q_{x,2}) \) is the observed event-plane, which is smeared around the true event plane, \( \Phi_2 \), due to the finite number of particles in an event. The magnitude of the \( \vec{q}_2 \) is used in the following for subdivision of each centrality interval into finer \( q_2 \) intervals as explained in [17]. The default analysis is obtained in the fourteen non-overlapping \( q_2 \) intervals, but for better precision, sometimes they are re-grouped into five wider \( q_2 \) intervals each containing 20% of the statistics.

Figure 6 shows the correlation of \( v_2 \) and \( v_n \), \( n = 2, 3, 4 \) for various centrality intervals. The \( x \)-axis represents \( v_2 \) values in 0.5 – 2 GeV range, while the \( y \)-axis represents \( v_2 \) for a higher \( p_T \) range (left) and \( v_3 \) and \( v_4 \) for the same \( p_T \) range. Each data point corresponds to a 5% centrality interval within the overall centrality range specified in the legend of the plots. Going from central collisions (left end of the data points) to the peripheral collisions (right end of the data points), the \( v_2 \) first increases and then decreases along both axes, reflecting the characteristic centrality dependence of \( v_2 \), well known from previous flow analyses. The rate of decrease of \( v_2 \) is larger at intermediate \( p_T \) (2 < \( p_T \) < 8 GeV), resulting in the boomerang-like structure in the correlation. The stronger centrality dependence of \( v_2 \) at higher \( p_T \) is consistent with larger viscous-damping effects expected from hydrodynamic calculations [18]. The boomerang-like structures in case of \( v_2 - v_3 \) correlation reflects mostly the fact that \( v_3 \) has a much weaker centrality dependence than \( v_2 \). However, at higher \( p_T \)

Figure 7: The correlation of \( v_2 \) in 0.5 < \( p_T \) < 2 GeV \((x\)-axis\) with \( v_2 \) in higher \( p_T \) range (left), and \( v_3 \) (middle) and \( v_4 \) (right) in the same \( p_T \) range \((y\)-axis\) [17]. In each panel, each flow harmonic is calculated in subsequent 5% centrality intervals in the centrality range 0 – 70% (left and middle) and 0 – 65% (right). The data-points for the most central and most peripheral centrality intervals are indicated explicitly. The error bars and shaded boxes represents the statistical and systematic uncertainties, respectively. These uncertainties are often smaller than the symbol size.

The thin solid straight lines in the right panel represent a linear fit of the data in each centrality. In the middle and right panel the thin lines are used only to connect the points in the same centrality interval. Error bars represent the statistical uncertainties.
(not shown), the decrease of v₃ for peripheral collisions is much more significant than that for v₂, and the turnover point of the boomerang changes from 40 – 50% centrality range at low p_T, and decreases to 30 – 40% centrality range at high p_T. This behaviour is consistent with stronger viscous-damping effects for v₃ than for v₂ for p_T < 3 GeV or for 0 – 50% centrality interval, as predicted by hydrodynamic models [19]. The boomerang-like structure in case of v₂ – v₄ correlation is less pronounced than in the v₂ – v₃ correlation, due to a significant non-linear contribution from v₂ that affects the v₂ – v₄ correlation.

The events in each centrality interval are then further sub-divided into q₂ intervals, as described above. With this further sub-division each data point in Fig. 6 turns into a group of data points, which may follow a different correlation pattern. Figure 7(left) shows the v₂ correlation between 0.5 < p_T < 2 GeV and 3 < p_T < 4 GeV and v₂ – v₃ and v₂ – v₄ correlations in the same 0.5 < p_T < 2 GeV range for different q₂ event classes. For clarity only selected centrality intervals are shown. In each panel the overall centrality dependence prior to the q₂ selection from Fig. 6 (the boomerang) is also shown. The v₂ correlation within a given centrality interval follows approximately a straight line pointing back very close to the origin. This approximately linear correlation suggests that, once the event centrality or the overall event multiplicity is fixed, the viscous-damping effects on v₂ changes very little with the variation of the event ellipticity via q₂ selection. The influence of viscous corrections on v₂ is mainly controlled by the event centrality (or the overall system size). Figure 7(middle) shows the v₂ – v₃ correlation in 0.5 < p_T < 2 GeV for different q₂ event classes overlaid with the centrality dependence taken from Fig. 6. The correlation within a fixed centrality interval follows a very different path than the centrality dependence: the v₂ and v₃ are always anti-correlated with each other within a given centrality, whereas they are positively correlated as a function of centrality. Since the v₂ and v₃ are driven by the initial eccentricities, one may expect similar anti-correlation between the two eccentricities. Indeed, recent calculations based on a multi-phase transport model [14] show that such anti-correlations exist in the initial geometry and they are transferred into similar anti-correlations between v₂ and v₃ by the collective expansion. Figure 7(right) shows the v₂ – v₄ correlation in 0.5 < p_T < 2 GeV for different q₂ event classes overlaid with the centrality dependence taken from the right panel of Fig. 6. The correlation within a given centrality interval is broadly similar to the trend of the correlation without q₂ selection, but without any boomerang effect. Instead, the shape of the correlation exhibits a power-law rise for large v₂ values. To further understand the role of the linear and non-linear contributions to v₄ and to separate them, the v₂ – v₄ correlation are fitted with the following functional form, separately for each centrality:

\[ v₄ = \sqrt{c_0^2 + (c_1 v₂^2)^2} \]  

(5)

The results as a function of centrality are shown in Fig. 8 (open circles and squares). The linear term depends only weakly on centrality, and becomes the dominant part of v₄ for N_{part} > 150 or 0 – 30% centrality range. The non-linear term increases as the collisions become more peripheral, and becomes the dominant part of v₄ for N_{part} < 120. Since the contributions of higher-order non-linear terms are small as suggested by the fits discussed above, the linear and nonlinear contributions can also be estimated directly from the previously published event-plane correlations \( v_{NL}^4 \). \( v_4 \) is the results of decomposition are also shown in Fig. 8, and they agree with the result obtained from direct fit.

6. Long range correlations in p+Pb collisions

An important tool to probe the collective phenomena in heavy ion collisions is two-particle correlation (2PC) function measured as a function of relative pseudorapidity (\( \Delta \eta \)) and azimuthal angle (\( \Delta \phi \)) of particle pairs. ATLAS has measured 2PC function and the first five azimuthal harmonics v₁ – v₅ in p+Pb collisions [20]. The 2PCs and vₙ coefficients are obtained as a function of p_T for pairs with 2 < |\( \Delta \eta \)| < 5 in different intervals of event activity, defined by either N_{rec}^{ch}, the number of reconstructed tracks with p_T > 0.4 GeV and |\( \eta \)| < 2.5,
or $E_T^{\mathrm{Pb}}$, the total transverse energy over $4.9 < \eta < 3.2$ on the Pb-fragmentation side.

Significant long-range correlations (extending to $|\Delta \eta| = 5$) are observed for pairs at the near-side ($|\Delta \phi| < \pi/3$) over a wide range of transverse momentum ($p_T < 12$ GeV) and broad ranges of $N_{\mathrm{ch}}^{\mathrm{rec}}$ and $E_T^{\mathrm{Pb}}$. A similar long-range correlation is also observed on the away-side ($|\Delta \phi| > 2\pi/3$), after subtracting the recoil contribution estimated using the 2PC in low-activity events. The azimuthal structure of these long-range correlations is quantified using the Fourier coefficients $v_n$, $n = 2 - 5$ as a function of $p_T$. The $v_n$ values increase with $p_T$ to $3 - 4$ GeV and then decrease for higher $p_T$, but remain positive in the measured $p_T$ range. The overall magnitude of $v_n(p_T)$ is observed to decrease with $n$. The magnitudes of $v_n$ also increase with both $N_{\mathrm{ch}}^{\mathrm{rec}}$ and $E_T^{\mathrm{Pb}}$. The $v_2$ values seem to saturate at large $N_{\mathrm{ch}}^{\mathrm{rec}}$ or $E_T^{\mathrm{Pb}}$ values, while the $v_3$ values show a linear increase over the measured $N_{\mathrm{ch}}^{\mathrm{rec}}$ or $E_T^{\mathrm{Pb}}$ range. The first-order harmonic $v_1$ is also extracted from the 2PC. The $v_1(p_T)$ function is observed to change sign at $p_T \approx 1.5 - 2.0$ GeV and to increase to about 0.1 at $p_T > 4$ GeV.

The extracted $v_2(p_T)$, $v_3(p_T)$ and $v_4(p_T)$ are compared to the $v_n$ coefficients in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with similar $N_{\mathrm{ch}}^{\mathrm{rec}}$. After applying a scale factor of $K = 1.25$ that accounts for the difference of mean $p_T$ in the two collision systems, the shape of the $v_n(p_T/K)$ distribution in Pb+Pb collision is found to be similar to the shape of $v_n(p_T)$ distribution in p+Pb collisions. This suggests that the long-range ridge correlations in high-multiplicity p+Pb collisions and peripheral Pb+Pb collisions are driven by similar dynamics.

7. Summary

Recent results from the ATLAS experiment related to the study of Quark-Gluon Plasma via ‘soft probes’ have been briefly presented. For more details and in depth discussion of the measurements the reader is refered to the original publications.

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References