Possible new studies to be considered in view of the upgrade of the LHCb detector.

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Introduction. This note summarizes three ideas of possible new analyses to be performed at the LHCb detector after its upgrade. The corresponding ideas are very recent and consequently require feasibility studies, first at the purely theoretical and subsequently at the experimental level. The three ideas touch two basic concepts, namely ultra-peripheral collision physics as well as electromagnetic effects ("strong fields") induced by the charge of the incoming nuclei. Ultra-peripheral collisions of nuclei are a broad field of studies presently realized at RHIC [1] and LHC [2]. Electromagnetic effects are connected to the well-known postulate of formation of an extremely strong magnetic field in heavy ion collisions, reaching $eB_y \approx m_\pi^2$ (~ 3 x 10^{14} T) at RHIC and $eB_y \sim 15\ m_\pi^2$ at LHC energies [3-5].

The three new areas of study are discussed below.

1. Lepton pair production in ultra-peripheral nucleus-nucleus collisions as a function of rapidity

Studies of ultra-peripheral collisions (UPC) made at the LHC benefit from the highest available cross sections for the corresponding processes, but at the same suffer from limited experimental acceptance in rapidity. The situation can be exemplified in the way presented in Fig. 1 (solid rectangle). The planned upgrade of the experimental set-up of the LHCb detector offers for the first time an extended coverage in lab rapidity ($2<y<5$) in the very low transverse momentum regime ($p_T<100$ MeV/*c*). Consequently, measurements of processes of the type Pb+Pb $(\gamma\,\gamma) \rightarrow e^+e^-$, resulting in the production of electrons/positrons at very low transverse momentum, can be performed in significantly broader ranges of final state rapidity with e^+ and e^- identification. This brings an evident advantage in view of the verification of the numerous corresponding models.

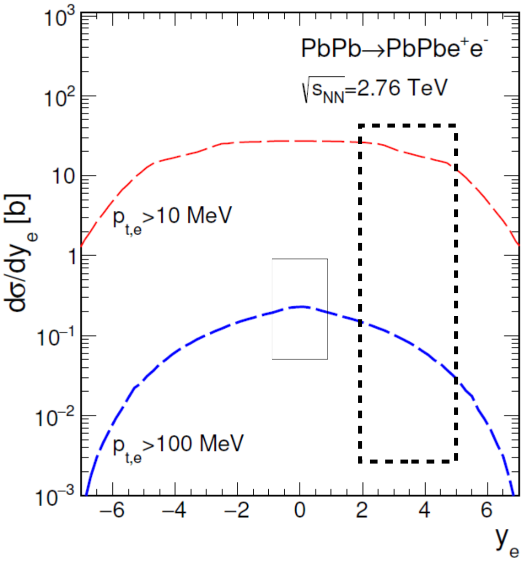

Fig. 2. Predicted differential cross section as a function of electron/positron rapidity. Results of our theoretical calculation [1] are presented for ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV. Red dashed line – $p_{T,e^\pm}$>10 MeV/*c*, blue dashed line - $p_{T,e^\pm}$ >100 MeV/*c*. The solid and fat dashed rectangles mark the (pseudo-)rapidity coverage of ALICE and the planned for the upgraded LHCb detector, respectively.

To take the example of the 1.58 TeV/nucleon Pb beam already used by the LHC experiment, in the collider mode for the ultra-peripheral Pb+Pb $(\gamma\gamma) \rightarrow e^+e^-$ reaction, electron/positron detection spans over the intermediate regime of Pb+Pb c.m.s. rapidity, half-way between the central regime (y=0) and that of the incoming Pb nucleus (ybeam ≈ 8). For the same beam with fixed target ("smog") mode taken for the Pb+Pb collision ($\sqrt{s_{NN}} \approx 54$ GeV), the same corresponds to $-2<y<1$ in Pb+Pb c.m.s. rapidity. What is particularly valuable is the good coverage at low transverse momentum, which is essential for detection of electrons/positrons from the Pb+Pb $(\gamma\gamma)$ process.

These advantages can be nicely illustrated if compared to a state-of-the-art example. The ALICE experiment measured e^+e^- production in UPC at $\sqrt{s_{NN}}=2.76$ TeV [2]. Outgoing particles were detected in the rapidity interval $-0.9<y_{e\pm}<0.9$. We note that experimental data are in agreement with models implementing QED at leading order [6]. The corresponding theoretically predicted differential cross section as a function of electron/positron rapidity is shown in Fig. 1, including two limits on the electron/positron transverse momentum $p_{T,e\pm}$. With a smaller cut on transverse momentum, the predicted distribution becomes flatter, which means that a lower $p_{T,e\pm}$ limit allows to obtain still a significant cross section in a more forward rapidity region. Account taken of the symmetric physical rapidity distribution, the experimental coverage planned after the upgrade of LHCb corresponds to an unknown up to now region of the $(y_{e\pm}, p_{T,e\pm})$ distribution, with ~3 times broader coverage in $y_{e\pm}$, and access to a completely new region of $p_{T,e\pm}$.

A further evaluation of this idea requires a proper theoretical evaluation of double differential cross sections $(d^2\sigma/dydp_T)$ for e^+e^- pair production as a function of collision type (nucleus-nucleus, proton-nucleus) and energy in view of the experimental capabilities and plans of the LHCb Collaboration. Once available, the latter cross-sections can be used to evaluate the potentially available statistics, significance over possible background, etc.

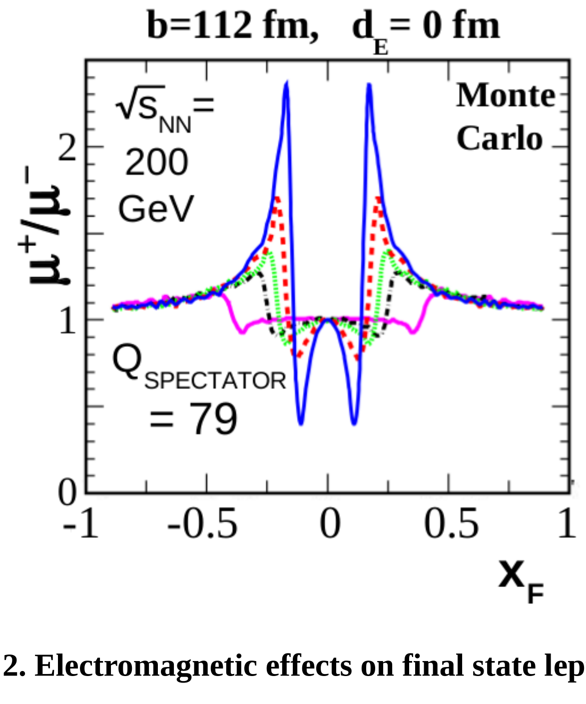

Fig. 2. Electromagnetic distortion of the ratio of postive over negative muons (μ^+/μ^-) produced in the ultra-peripheral Au+Au $(\gamma\gamma) \rightarrow \mu^+\mu^-$ reaction, drawn a function of the muon x_F for fixed values of p_T (blue solid: 25 MeV/*c*, red dash: 75 MeV/*c*, green dot: 125 MeV/*c*, black dash-dot: 175 MeV/*c*, solid magenta: 225 MeV/*c*). The Monte Carlo simulation is performed for a single set of initial conditions with the $\mu^+\mu^-$ produced a the impact parameter b=112 fm and at the moment of closest approach of the two nuclei which corresponds to the longitudinal distance $d_E=0$ of the muon pair emission site from the spectator system along the z axis. To appear in [7].

2. Electromagnetic effects on final state lepton pair emission in ultra-peripheral collisions

A more sophisticated version of the measurement described above is the possibility of investigating the final state electromagnetic (EM) effects on the spectra of e^+e^- pairs produced in the UPC reaction Pb+Pb $(\gamma\gamma) \rightarrow e^+e^-$ (or any similar process). In view of the experimental limitations of existing detectors such effects were up to now studied by us only theoretically, but they can be regarded as a direct consequence of the long-range character of the EM field induced by ultrarelativistic ions. An example is presented in Fig. 2, which shows the final state μ^+/μ^- ratio of positive over negative muons created in the ultra-peripheral Au+Au $(\gamma\gamma) \rightarrow \mu^+\mu^-$ reaction at top RHIC energy, $\sqrt{s_{NN}}$=200 GeV. The ratio is drawn as a function of the Feynman x_F and p_T of the muon. Large distortions, including in particular a dip in the μ^+/μ^- ratio in the vicinity of Au nucleus velocity ($x_F = m_\mu/m_N \approx 0.11$) and low p_T are evident. The origin of this effect which was up to now measured for ratios of charged pions at SPS energies [8-10], is that the $\mu^+\mu^-$ pair is created in a persisting EM field induced by the charge of the two nuclei, and consequently muon trajectories are modified as a function of initial muon x_F and p_T . As indicated in our earlier work [11], this effect is sensitive to the space-time evolution of the process of production of the emitted particle(s), and therefore it could potentially bring completely new information on the UPC dynamics in both momentum and position space. This is even more valuable in view of the limitations of the current theoretical approaches which remain largely restricted to momentum space alone [12].

Several introductory studies are indicated before the above idea can be considered as realizable. These include (1) theoretical evaluation of double-differential cross-sections for the Pb+Pb $(\gamma\ \gamma) \rightarrow e^+e^-$ process (or similar, including also proton-nucleus), consistently with what was addressed in **1.** above, (2) realistic theoretical calculations of final-state EM effect on e^+e^- pair emission, taking account of the lack of experimental information on impact parameters and space-time conditions for UPC processes (please note that the plot shown in Fig. 2 is only an example taken for specific initial conditions), and (3) definition of best observables to study.

It should be noted that the easiest measurement of the direct electromagnetic distortion of e^+/e^- ratios as it was done π mesons [8-11] does not seem realistic in the case of the LHCb. This is because it requires low-p_T acceptance close to the incoming nucleus rapidity. To give two examples, for the case of the 1.58 TeV/nucleon Pb beam moving into the acceptance of the LHCb detector, the Pb nucleus remains ~3 units of rapidity out of the upgraded LHCb coverage ($2<y<5$). At the same time the fixed “smog target” nucleus preserves a gap of 2 units of rapidity, but with no coverage at low p_T. Thus altogether, a direct measurement of the e^+/e^- ratio distortion similar to that shown in Fig. 2 seems conceivable only for Pb beam momenta significantly lower than 1.58 TeV/nucleon.

However, as it was shown by us for charged pion emission in inelastic Pb+Pb collisions, *angular* distortions may provide more promising observables for the LHCb set-up. For charged pions produced in heavy ion collisions, a useful observable appeared to be the sidewards deflection of pions in the reaction plane [13]. In analogy, distortions in the opening angle of the e^+e^- pair produced in the UPC process can be a good candidate to investigate in view of final-state EM effects [14].

It seems clear that conceptual preparatory work following the lines (1)-(3) above, including theoretical calculations made for selected observables, is indicated here. Once the corresponding theoretical analyses are achieved, they can serve as a starting point for the corresponding feasibility studies on the experimental side.

3. Charge splitting of directed flow in nucleus-nucleus and proton-nucleus collisions

The study of charge dependence of the sidewards deflection of particles (directed flow) can be used to investigate the effects induced by the very strong electric and magnetic fields induced in the heavy ion collision [15], specified as “probably the strongest magnetic field in the present universe” [16].

Specifically, the magnitude of charge splitting of directed flow of opposite charge particles (like π^+ and π^- mesons) can provide information on the space-time evolution of the reaction [17]. First predictions for such effects on directed flow known to us are [13,18]. Data on this effect exist from STAR [19]. A first attempt at such studies has been just released by ALICE [20]. All these measurements are made for symmetric (Au+Au, Pb+Pb) collisions and limited to the central region of rapidity which following our theoretical work is the region where the magnitude of the corresponding effect will be minimal (see Fig. 3 and discussion made in Ref. [13]).

The upgraded set-up of the LHCb detector could bring a considerable improvement in the experimental situation by extending the available range of rapidity, bringing it closer to the nuclear spectator system where we predict and enhancement of charge splitting of directed flow. In particular, a comparison between Pb+Pb and p+Pb as well as Pb+p collisions is possible where the latter two reactions do not suffer from a possible cancellation of the EM induced by the two spectator systems (Fig. 3). Consequently, charge splitting effects much stronger than these available at ALICE, and consequently a higher chance of obtaining information on the space-time evolution of the system, may become available from LHCb.

Depending on the exact outcome of the preparatory theoretical work on the reactions enumerated above including also more detailed information on detector acceptance and particle identification as a function of rapidity and p_T, the measurement of charge splitting of directed flow can be considered both in the collider and fixed target data taking modes. To take the example of the incoming Pb beam at 1.58 TeV beam energy moving in the direction of the LHCb acceptance, the upgraded LHCb coverage extends up to -3 units of rapidity from the projectile spectator system, which is 5 units of rapidity from the collision c.m.s. in the symmetric collider mode ($\sqrt{s_{NN}}$ = 3.16 TeV), or 1 unit of rapidity in the fixed target mode ($\sqrt{s_{NN}} \approx$ 54 GeV). The lower lab rapidity limit corresponds, for the fixed target mode, to 2 units of rapidity from the target spectator system and -2 units from the collision s.m.s. As a result different regions of rapidity and different magnitudes of the effect can be probed as a function of system size and collision energy, but theoretical guidance is needed in order to select the optimal system/energy configuration(s) for feasibility studies.

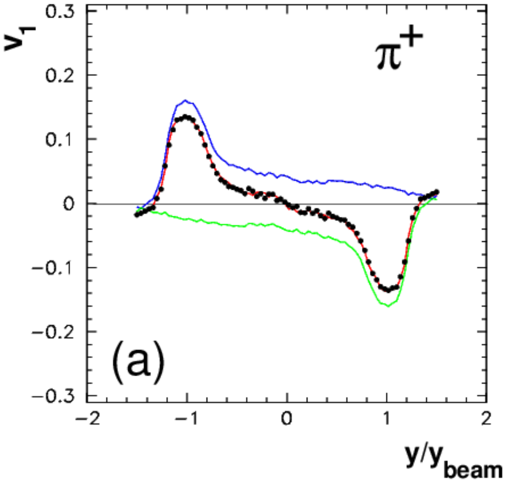

Fig. 3. Pure EM effect induced on directed flow ($v_1 \equiv \langle\cos(\phi)\rangle$, where ϕ is the pion angle w.r.t. the reaction plane) for positive pions produced in peripheral (inelastic) Pb+Pb collisions at $\sqrt{s_{NN}} \approx$ 17.3 GeV, drawn as a function of normalized pion c.m.s. rapidity. The effect is induced either by one (blue solid, green solid) or by two (red solid, dots) spectator systems. From Ref. [13].

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