VERY FORWARD TWO–PHOTON e^+e^- PRODUCTION AND LUMINOSITY MEASUREMENT FOR ION COLLISIONS AT THE LHC

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A possible way of using two-photon very forward production of positron–electron pairs for a luminosity measurement of ion collisions at the LHC is discussed. The main characteristics of this process are introduced, and followed by results from fast Monte Carlo simulations of the measurement using the proposed Castor detector. The statistical accuracy of this method is discussed for the considered LHC ion beams.

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1. Introduction

The possibility of using two-photon processes for luminosity measurements at hadron colliders was first considered in [1,2]. The cross-section for very forward two-photon production of e^+e^- pairs in proton–proton collisions can be calculated within QED to a very high accuracy, especially at the LHC energies for which the high energy approximation can be used in the calculations [3]. Therefore, measuring these pairs could allow for a precise

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luminosity determination at the LHC. That has been already considered for the pp collisions [4], and in this work application of such a technique for ion collisions at the LHC is discussed. One should note that in this case no well established methods are available to normalize the AA luminosity.

2. Characteristics of the forward pair production

The main characteristics of the reaction $pp \to pp\, e^+e^-$ are the very small (of the order of the electron mass) invariant mass, $M_{e^+e^-}$, and transverse momentum, p_{T}, of the produced pairs (see Fig. 1). In addition, the acoplanarity angle φ is close to zero, $\varphi \approx p_{\mathrm{T}}/p_{\mathrm{T}}^{(-,+)}$, where $p_{\mathrm{T}}^{(-,+)}$ is the transverse momentum of an electron, or a positron. In contrast, in the case of the pair production in the *inelastic* two-photon process, where one or both protons break up, the distribution of p_{T} is significantly wider, as well as for hadronic reactions, where the typical energy scale is the pion mass or higher, rather than the electron mass. This characteristics corresponds to a very small emission angles of the produced electrons and positrons, with respect to the colliding protons. For example, for energies of a few GeV the typical angles are of the order of 1 mrad. Detection of such events requires, therefore, detectors which are installed very close to the proton beam.

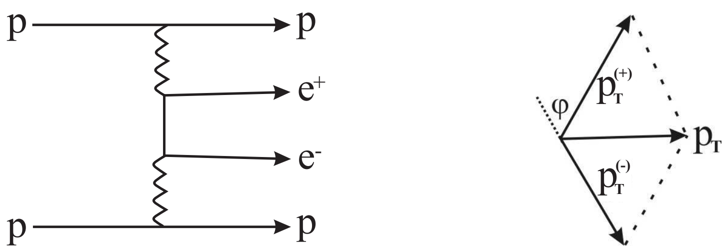

Fig. 1. Feynman diagram of the two-photon process; variables defined in the transverse plane are introduced — the transverse momentum of a pair, p_{T}, and the acoplanarity angle, φ, which is an azimuthal angle between the transverse momenta of the produced electron and positron.

The ATLAS and CMS experiments plan to study both the proton and ion collisions at the LHC, therefore, the issue of the ion luminosity measurement has to be addressed. The usual method of the pp luminosity normalization using the optical theorem and elastic and inelastic hadronic interactions is not applicable here due to experimental difficulties, in particular necessity of measuring the elastic ion scattering at extremely small angles. In this context, the two-photon e^+e^- pair production is particularly interesting because the two-photon interactions in ion collisions are enhanced owing to the coherence effects [5]. For forward pair production this enhancement scales as Z^4, whereas the hadronic backgrounds scale approximately as A^2, where A and Z are atomic numbers of the colliding ions (here collisions of same ion species were assumed). In addition, the inelastic two-photon production is suppressed in the coherent ion interactions [6]. The full coherence is ensured for the very forward two-photon process $AA \to AA\ e^+e^-$ thanks to very small virtualities of the exchanged photons. In other words, this process usually occurs at distances where ions can be regarded as point-like particles having charges equal to Z.

The backgrounds to the two-photon pair production in *pp* collisions can be strongly reduced, with remaining two dominant components due to the Dalitz decays of π^0 and the pair production via bremsstrahlung process in hadronic interactions [7]. These two hadronic backgrounds will be, therefore, even more suppressed in the ion collisions, because in this case the signal to background ratio is expected to be significantly better than in the *pp* collisions.

3. Fast simulation of the measurement using the Castor detector

Recently, Castor, a new detector in the forward region has been proposed for studies of the ion collisions in the CMS experiment. Below, the following performance of this detector is assumed in fast simulations of the forward pair measurement: the Castor (geometrical) angular acceptance, extending between 2.2 and 8.2 mrad, and relative energy resolution of $20\%/\sqrt{E}$, where energy E is given in GeV [8]. To measure precisely the position of the charged particles hitting Castor, usage of the Totem T2 telescope, with a spatial resolution of 70 μm [9], is proposed. Since, this aspect is not yet fully developed, a conservative spatial resolution of 0.5 mm has been assumed below.

In the following simplified simulations only the Gaussian resolutions are used, with the quoted widths, to smear the "true" variables. In addition, the smearing due to the ion beam angular divergence and spatial distribution at the interaction point are taken into account. All quoted results, presented further in the text, correspond to an energy range for electrons and positrons of 3–20 GeV. The lower energy limit is a compromise between the need for a maximal cross-section and the good performance of Castor, while the upper limit is rather arbitrary and affects the results very little, even if it is significantly increased.

The Lpair event generator is used for the simulation of the two-photon process [10]. This is a leading order, Born-level, generator initially constructed for proton interactions. Because of the Born approximation its results cannot be trusted if the product of two ion charges exceeds significantly 137. Therefore, we present mostly results obtained for proton–ion collisions and light ion collisions, where the higher order corrections, in particular the so-called Coulomb corrections should be at most at the 1% level [11]. The heavy ion case is not discussed in detail here, and requires another approach — the Coulomb corrections, for example, result in a 11% decrease of the cross section [12]. The LPAIR generator has been modified to allow for ion collisions by scaling the charges of the colliding particles by Z, and by increasing the radius of the charge distribution by $A^{1/3}$ with respect to the nominal proton case. The same shape, though, of the electromagnetic form factor, according to the so-called dipole approximation, has been assumed. In this approximation:

$$G_{\mathrm{E}} = \frac{G_{\mathrm{M}}}{\mu_p} = (1 + Q^2 R_p^2)^{-2}, \tag{1}$$

where G_{E} and G_{M} are the electromagnetic formfactors, Q^2 is the photon virtuality, and $R_p^2 = 1/0.71\mathrm{GeV}^2$ is the proton radius squared.
Hence, for the ion collisions the ion radius R_A is given by:

$$R_A = R_p A^{\frac{1}{3}}. \tag{2}$$

The cross section calculations depends however very little on the actual form of R_A. If, for example, R_A scales as $A^{1/2}$, or as $A^{1/4}$, the result changes by less than per mille. This is just a manifestation of very small photon virtualities involved.

The simulations were done for the nominal energies of 7, 140 and 574 TeV for the proton, calcium and lead beams, respectively.

4. Results

Table I shows the results of the simulation with the modified LPAIR program assuming the nominal CASTOR calorimeter acceptance and performance. A simple reconstruction procedure has been implemented, and the values in brackets correspond to the results obtained when the cuts were done using the reconstructed variables. The results with the cuts applied on the transversal pair momentum, pair invariant mass and acoplanarity angle are shown in the column 2–4. The definition of the applied cuts 1, 2 and 3 are as follows:

- cut 1 — $2.23 < \Theta < 8.17$ mrad, 3.0 GeV$< E < 20.0$ GeV
- cut 2 — $p_{\mathrm{T}} < 30$ MeV, $M_{e^+e^-} < 70$ MeV
- cut 3 — $|\varphi| < 60^\circ$

TABLE I

The cross sections for three types of ion collisions calculated using the modified LPAIR program after applying the acceptance and selection cuts. The values in the brackets show the results after smearing of the production vertex and angle, and obtained using the reconstructed variables.

Cuts	1	$1 \cap 2$	$1 \cap 2 \cap 3$
Ca–p	29.08 (29.16) μb	21.28 (21.32) μb	18.22 (18.19) μb
Ca–Ca	11.62 (11.71) mb	9.40 (9.43) mb	7.31 (7.33) mb
Pb–p	0.41 (0.41) mb	0.34 (0.34) mb	0.26 (0.26) mb

In Fig. 2 distributions of the transverse momentum, the invariant mass and acoplanarity angle of the e^+e^- pairs produced in calcium–proton collisions and detected in CASTOR are shown. The acoplanarity distribution shows the peak around zero, unique for the two-photon production, where about 80% events are contained within an interval $\pm 60°$. Moreover, the $p_{\rm T}$ distribution is very narrow with majority of events with $p_{\rm T} < 10$ MeV.

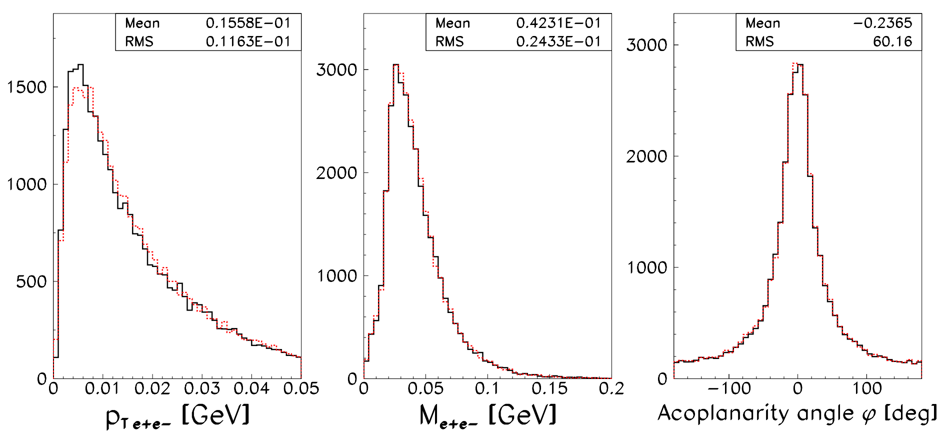

Fig. 2. Distributions of the transverse momentum, invariant mass and acoplanarity angle of the forward (along the ion beam direction) pairs produced within the CASTOR acceptance in calcium–proton collisions. The dashed histograms show the reconstructed distributions.

The reconstructed distributions (overlaid dashed histograms) are very close to the true ones, demonstrating the adequate performance of CASTOR. The results of simulations are very similar for the p–Ca cases, both in terms of the cross sections and the shape of distributions.

In Fig. 3 the same distributions are shown for the case of calcium–calcium collisions. They exhibit very similar features to the p–Ca case.

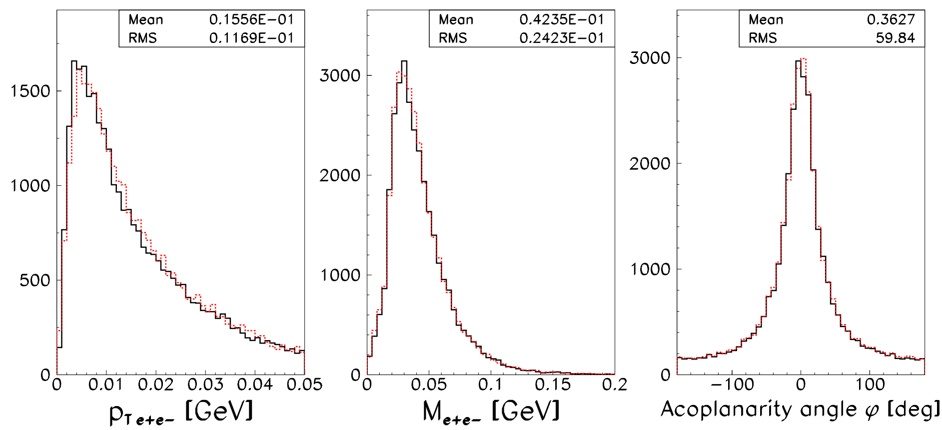

Fig. 3. Distributions of the transverse momentum, invariant mass and acoplanarity angle of the pairs produced within the CASTOR acceptance in calcium–calcium collisions. The reconstructed distributions are overlaid as dashed histograms.

Finally, the same distributions are shown for the proton–lead collisions and can be seen in Fig. 4. They are similar to both previous cases.

As discussed previously in the context of the pp luminosity measurement, the distribution of acoplanarity angle and $p_{\rm T}$ is a unique signature of the (elastic) two-photon pair production and is a key factor in the precise luminosity determination. It is, therefore, crucial to see if the detector-reconstructed variables still exhibit the observed properties, *i.e.* if the detector resolutions do not smear-out the signature of this process. In Figs. 2–4 the distributions of the reconstructed variables assuming the CASTOR performance are shown (dashed line). It demonstrates that the efficient selection of the luminosity events can be achieved.

From the point of view of statistical precision, the effective rate of luminosity event is crucial. In Table II are shown: the "observed" cross-sections, obtained by requiring the produced pairs to be detected in CASTOR, and the time which is needed to collect a sample of ten thousand events (or to obtain a 1% statistical precision), for corresponding nominal luminosities of ion collisions at the LHC. It clearly demonstrates that the detection of

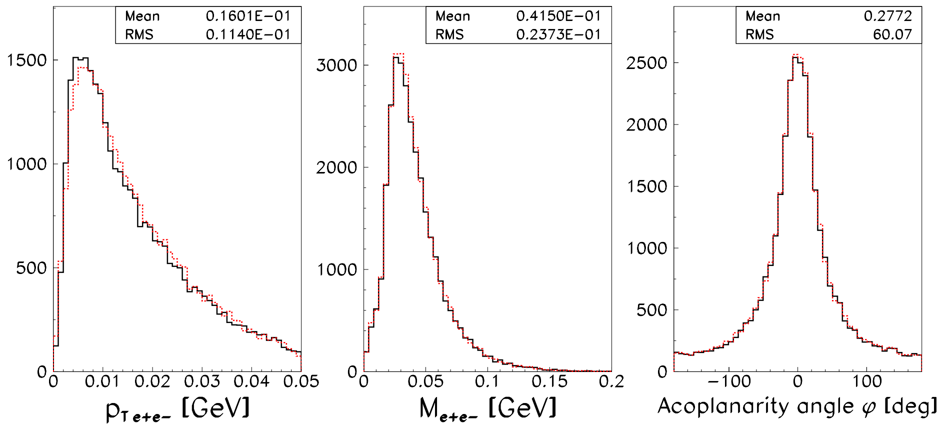

Fig. 4. Distributions of the transverse momentum, invariant mass and acoplanarity angle of the forward (along the ion beam direction) pairs produced within the CASTOR acceptance in lead–proton collisions. The reconstructed distributions are overlaid as dashed histograms.

very forward e^+e^- pairs in CASTOR should allow not only a precise (and absolute) measurement of the LHC luminosity but also fast on-line luminosity monitoring. Further studies of the systematic uncertainties and more detailed experimental aspects of the luminosity measurement using forward lepton pairs, including the possibility of using CASTOR to measure also the *pp* luminosity at the LHC, will be published elsewhere [13].

TABLE II

Results for four types of ion collisions: the observed cross-section using the CASTOR detector; the expected ion luminosities in ATLAS and CMS, and the time needed to collect 10^4 luminosity events.

Collision type	$\sigma_{\rm obs}$ [mb]	L [cm^{-2}/s]	$T_{1\%}$ [s]
Ca–Ca	7.31	10^{29}	14
Ca–p	18.2×10^{-3}	10^{31}	55
Pb–p	0.26	10^{30}	39
Pb–Pb	$\approx 1.67 \times 10^3$	10^{27}	6

5. Conclusions

In summary, the measurement of the forward two-photon production of e^+e^- pairs will allow a precise and fast luminosity determination for all planned types of ion collisions at the LHC. The recently proposed Castor detector seems to be a very good candidate for that purpose, and should give a unique opportunity of using the same technique to normalize the LHC luminosity.

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