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Precision luminosity measurement at LHC using two-photon production of $\mu^+\mu^-$ pairs.

A.G. Shamov, V.I. Telnov

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia
A.G.Shamov@inp.nsk.su, V.I.Telnov@inp.nsk.su

Abstract

The application of the two-photon process $pp \to pp + \mu^+\mu^-$ for the luminosity measurements at LHC with the ATLAS detector is considered. The expected accuracy of the absolute offline luminosity determination is $1 \div 2$ % for the luminosity range of $10^{33} \div 10^{34}$ cm^{-2} s^{-1}. The preliminary cross section estimates done for LHCb promise the same level of the luminosity measurement accuracy at $L = 2 \cdot 10^{32}$ cm^{-2} s^{-1}.

Key words: luminosity measurement, two photon processes

1 Introduction

The possibility to use the two-photon pair production for luminosity measurements at hadron colliders was first considered in [1]. It was shown that the cross section of the process $pp \to pp + e^+e^-$ for the forward region can be calculated within QED with an accuracy of 1% or better allowing for a precise luminosity determination using the number of events observed and the calculated cross section: $L = N^{obs}/\sigma^{obs}$.

The method suggested in [1] provides for both the high rate monitoring and the absolute luminosity measurements but requires a dedicated apparatus allowing for the e^+e^--pair detection in the pseudorapidity range of $|\eta| > 5$ and capable

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[1] Talk at the VIII Intern. Conference on Instrumentation for Colliding Beam Physics, Novosibirsk, Russia, Feb. 28-March 6, 2002

of the p_T measurements with the accuracy of a few MeV. This approach has never been used. The kinematic domain of the central rapidity pairs is much more attractive from the experimental point of view though the corresponding cross section is smaller and some additional theoretic uncertainties appear.

The application of the centrally produced e^+e^--pairs with $p_T = 0.4 \div 1$ GeV for luminosity measurements at LHC with ATLAS was proposed in [2,3]. The detail study of the trigger issues and the background conditions has shown that using of $pp \to pp + \mu^+\mu^-$ with high-p_T muons looks favorable.

Due to the high p_T threshold of LHC experiments (≥ 1 GeV), the cross section of $pp \to pp + \mu^+\mu^-$ is small ($1 \div 15$ pb) therefore this process can not be used for the luminosity monitoring but provides for the absolute calibration of any stable high-rate monitor with the statistical accuracy of $1 \div 2$ % after of a few months operation.

Below the proposal for the ATLAS offline luminosity determination using the two-photon production of $\mu^+\mu^-$-pairs [4,7,5] is reported and the preliminary signal and background cross section estimates for the LHCb detector are presented.

It should be mentioned that the application of the forward e^+e^--pairs is under study in ATLAS [6,7,5]. The possibility to employ $pp \to pp + \mu^+\mu^-$ for luminosity measurements was manifested in [8] without a detail consideration of theoretical uncertainties and detector related questions.

2 On possibility of the cross section calculation

A review of the two-photon leptoproduction can be found elsewhere [9]. Main features of this process can be illustrated in the Equivalent Photon Approximation (E.P.A.) allowing one to express its cross section via the cross section of the pair production by virtual photons with the equivalent photon spectra

$$d\sigma = \sigma_{\gamma^*\gamma^* \to LL}\, dn_1\, dn_2 \tag{1}$$

For colliding leptons one has [9]

$$dn_{QED} = \frac{\alpha}{\pi}\frac{d\omega}{\omega}\frac{dq^2}{q^2}\left(1 - \frac{q^2_{min}}{q^2}\right) = \frac{\alpha}{\pi}\frac{d\omega}{\omega}\frac{\mathbf{q}_T^2\, d\mathbf{q}_T^2}{\left(\omega^2/\gamma^2 + \mathbf{q}_T^2\right)^2} \tag{2}$$

where $q\,(\omega, \mathbf{q})$ is the four-momentum of the virtual photon and $\gamma = E/m$ is the Lorentz factor of the colliding particle (we assume $\omega \ll E$).

The cutoff of the spectrum (2) occurs at $|\mathbf{q}_T| \sim W$ due to the q^2 dependence of $\sigma_{\gamma^*\gamma^* \to LL}$ (W is the invariant mass of the pair produced). The characteristic value of the the total transverse momentum of the pair produced $p_T \sim (\omega_1 + \omega_2)/\gamma \sim 10$ MeV in the luminosity measurements context.

When pp collide, the proton can dissociate during the photon emission therefore the elastic and the inelastic two-photon processes should be distinguished.

In the elastic case Fig. (1,a) only the small modification of the equivalent photon spectrum is required:

$$dn_{el} = dn_{QED} \times \frac{G_E^2 - q^2/4m_p^2\, G_M^2}{1 - q^2/4m_p^2} \tag{3}$$

(G_E, G_M are the electromagnetic form factors).

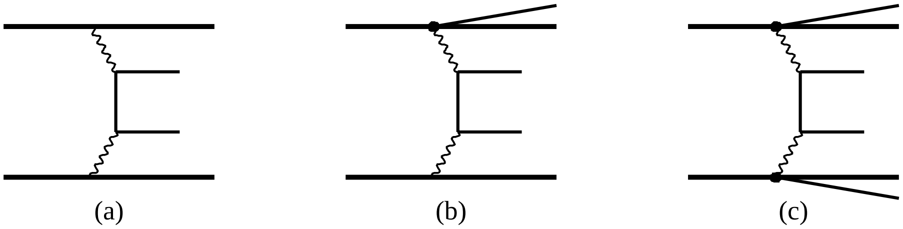

Fig. 1. Two-photon production of lepton pairs in pp collisions: (a) - elastic, (b,c) - inelastic

For the inelastic processes Fig. (1,b), (1,c) one has for each inelastic vertex [9,1]

$$dn_{inel} = dn_{QED} \times \frac{W_2(q^2, M^2)}{2m_p}\, dM^2 \approx dn_{QED} \times \frac{|q^2|}{4\pi^2\alpha}\, \frac{\sigma_T^{\gamma p} + \sigma_S^{\gamma p}}{M^2 - m_p^2}\, dM^2 \tag{4}$$

where M is the invariant mass of the hadronic system, W_2 is the inelastic scattering structure function and $\sigma_T^{\gamma p}$, $\sigma_S^{\gamma p}$ are the γp cross sections known from the photo- and electro-production experiments. Unlike (2) and (3), the expression (4) is not singular for $q^2 \to 0$ thus the characteristic pair p_T for the inelastic production is not small ($\sim$ 250 MeV).

Diagrams of Fig. 1 reflect the strong interaction inside the single proton, besides, the strong interaction between colliding protons, so called *rescattering*, should be taken into account (Fig. 2).

In the ATLAS luminosity measurement context, the rescattering has been considered in [10]. It was shown that the elastic strong interaction Fig. (2,b) just modifies the phase of the matrix element and does not change the cross section. The inelastic strong interaction Fig. (2,c) reduces the yield of $pp \to pp + \mu^+\mu^-$ on behalf of $pp \to X + \mu^+\mu^-$. In the experimental setup when only the muon pair is detected, the total dimuon cross section remains unchanged. To reduce the dimuon background from Drell-Yan process and the hadron

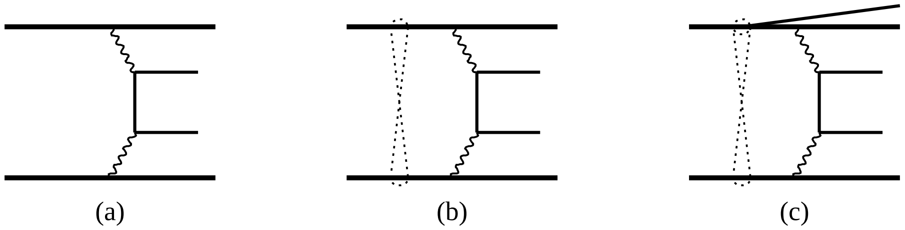

Fig. 2. Modification of the elastic two-photon process by rescattering (final state rescattering is not shown).

decays, the absence of extra particles in the dimuon vertex is necessary. In this case

$$\sigma_{\gamma\gamma}^{pp\to X+\mu\mu} = \sigma_{\gamma\gamma}^{el} + \epsilon_{inel}\cdot\sigma_{\gamma\gamma}^{inel} - (1-\epsilon_{rescat})\cdot\sigma_{\gamma\gamma}^{rescat} \tag{5}$$

where $\epsilon_{inel}, \epsilon_{rescat}$ are the probabilities that the event passes the vertex cut; for LHCb and ATLAS $\epsilon_{inel}, \epsilon_{rescat} > 0.8$.

The first two terms can be estimated using the E.P.A. formulae

$$d\sigma_{\gamma\gamma}^{el} = dn_{el,1}\, dn_{el,2}\ \cdot \sigma_{\gamma\gamma\to\mu^+\mu^-} \tag{6}$$

$$d\sigma_{\gamma\gamma}^{inel} = (dn_{el,1}\, dn_{inel,2} + dn_{inel,1}\, dn_{el,2} + dn_{inel,1}\, dn_{inel,2})\cdot\sigma_{\gamma\gamma\to\mu^+\mu^-} \tag{7}$$

$\sigma_{\gamma\gamma}^{inel} \sim \sigma_{\gamma\gamma}^{el}$ for the pair mass $W > 1$ GeV in absence of cuts on the total pair p_T.

The $\sigma_{\gamma\gamma}^{rescat}$ can not be expressed in terms of the equivalent photon spectra. Numerically, $\sigma_{\gamma\gamma}^{rescat} \sim 0.1\%$ of $\sigma_{\gamma\gamma}^{el}$ for p_T(pair) < 30 MeV [10].

The M.C. calculations performed by us for the ATLAS conditions has demonstrated that $\sigma_{\gamma\gamma}^{rescat} \sim 0.1\,\sigma_{\gamma\gamma}^{inel}$ and its dependence of on the pair p_T is similar to that of $\sigma_{\gamma\gamma}^{inel}$. So, it causes no additional problems for the luminosity measurements. Below we include the rescattering effect in the inelastic cross section.

It should be noted that the rescattering for the inelastic diagrams (1,b), (1,c) is not considered in [10] and is ignored in our cross section calculations. This and the bad knowledges of the soft inelastic scattering structure functions make the inelastic cross section estimates rather uncertain.

For the forward e^+e^--pair production the smallness of the pair mass W ensures the smallness of q^2 and makes the inelastic contribution negligible as was stated in [1]. The situation is not so simple concerning the muon pair production with $p_T(\mu) > 6$ GeV and $W > 12$ GeV. In this case the inelastic background is not negligible even with severe experimental cuts (see Fig. 3). However, the distributions of the pair p_T and related variables are very different allowing one to reduce the background to an acceptable level and then subtract it as described below.

The uncertainty in the residual inelastic contribution is about 30%, $\sim 3\%$ of the visible signal, does not affect the luminosity measurement due to the background subtraction. The accuracy of the elastic signal calculation $\leq 0.5\%$ is limited by the accuracy of the proton form factors only.

The formulae (6), (7) are presented above just for the illustration. The actual calculations were performed using the event generator [11] implementing the exact lowest order matrix element. The muon bremsstrahlung, affecting the essential parameter distributions, was simulated in the soft photon approximation; other types of radiative corrections were not applied. It seems sufficient for the current stage of the work.

3 Procedure for signal extraction

The following criteria are proposed for the ATLAS event selection:

(1) Two muon tracks of opposite charges (measured in both the Inner Detector and the muon spectrometer and triggered by the Muon systems) with $p_t > 6$ GeV and $|\eta| < 2.2$;
(2) Muon pair invariant mass < 60 GeV (against Z^0);
(3) p_T of the muons are equal within 2.5σ of the measurement uncertainty ($\sigma(p_T)/p_T \simeq 1.5\%$ for $p_T < 20$ GeV);
(4) Acollinearity angle $\Theta > 1°$ so the muons are not exactly back-to-back (against the cosmic ray background);

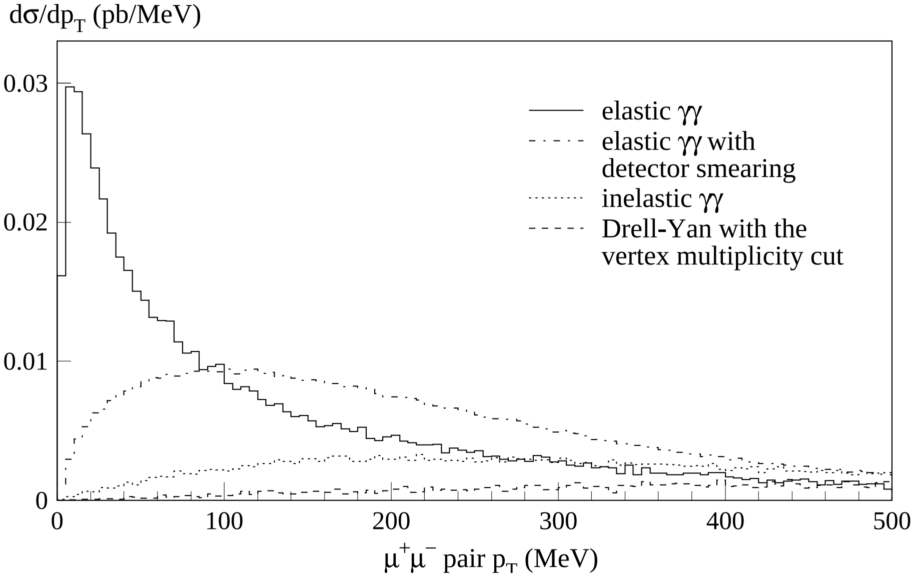

Fig. 3. The differential dimuon cross section $d\sigma/dp_T$ for $pp \to pp + \mu^+\mu^-$ as a function of the pair transverse momentum p_T (ATLAS, $W > 12$ GeV, $|\eta| < 2.3$).

(5) Probability of $\chi^2 > 1\%$ for the muon vertex fit;

(6) No other charged tracks with $p_t > 0.5$ GeV, $|\eta| < 2.5$, $\sigma(z_v) < 1$ mm and a good χ^2 from the muon vertex ($\sigma(z_v)$ is the estimated error in z for the nearest point to the beam).

The condition (6) strongly reduces the background from Drell Yan process and hadron decays but makes the detection efficiency dependent on the event pile-up probability. For the longitudinal LHC bunch size of 7.5 cm and the luminosity $L = 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, the loss of two-photon events is about 3%.

The expected acoplanarity distribution for selected events in shown in Fig. 4. (the acoplanarity angle ϕ is defined as the angle between the muon production planes). The simulation was performed using the particle level Monte Carlo code [4] with the detector properties parameterized according to the ATLAS specification. The signal and background cross section estimates for the reference region $|\phi| < 5$ mrad containing about 50% of the signal are presented in Table 1.

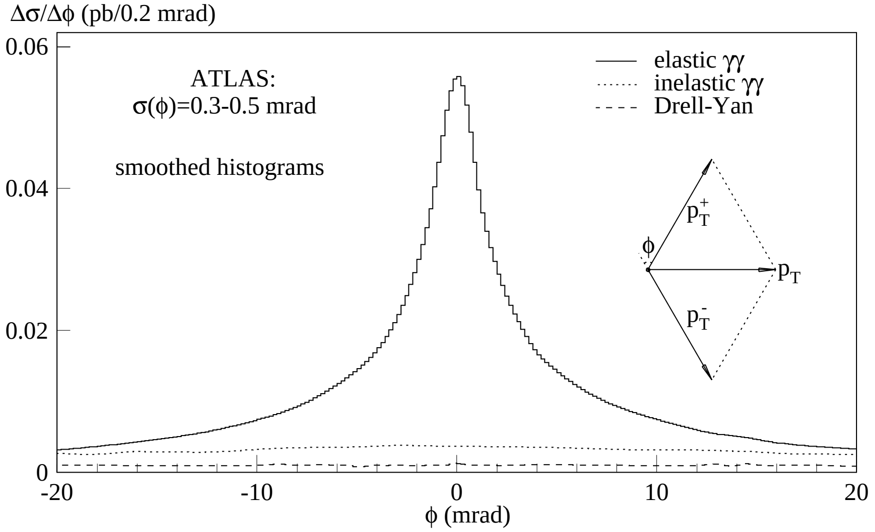

Fig. 4. The acoplanarity distributions for the signal and dominant background processes with all cuts applied.

The acoplanarity distribution has the sharp signal peak at $\phi = 0$ and is almost uniform for background processes in the range of $|\phi| < 50$ mrad. Unlike the distribution of the pair transverse momentum, it is not much affected by the detector resolution. Using this, the final signal extraction can be performed by fitting the ϕ distribution in the range of $\pm 20 \div 40$ mrad with the signal shape obtained by Monte Carlo and the symmetric parabolic background $A - B\phi^2$.

With the proper modification of the event selection criteria and the background subtraction ϕ interval, the procedure describe above can be employed in CMS and LHCb experiments.

Table 1
ATLAS cross section estimates for the kinematic cuts (1-4) and all cuts (the expected detection efficiency ≥ 0.65 is not taken into account).

process	σ_{kin}, *pb*	σ_{all}, *pb*
signal	1.33	1.30^{a}
$\gamma\gamma$(inelastic)	0.13	0.12^{b}
Drell-Yan process	4.0	0.04
Heavy quark decays	10.	0.01
π/K decays	1.8	<0.001
background	15.9	0.17 (13%)

a) for $L = 10^{33}$ cm^{-2} s^{-1}
b) including rescattering effect

4 On accuracy of ATLAS luminosity determination

The expected statistical accuracy of the luminosity determination $\approx 1.5\%$ for the integrated luminosity of 10 fb^{-1} (about 4 months of operation at $L = 10^{33}$ cm^{-2} s^{-1}) and the detection (trigger and reconstruction) efficiency of 0.65.

The systematic errors due to the uncertainty in the proton form factors and the background subtraction procedure are expected to be $\leq 0.5\%$. The pile-up correction can be done using the experimental data. The systematic error should not exceed 1% at $L = 10^{34}$ and is negligible at $L = 10^{33}$ cm^{-2} s^{-1}.

The uncertainty of the detection efficiency seems dominating source of the systematic error. This efficiency can be determined experimentally using the $pp \to pp + \mu^+\mu^-$ event sample with the accuracy better than 1% (it can be keep clean enough with some selection criteria relaxed). For the low luminosity operation ($L = 10^{33}$ cm^{-2} s^{-1}) the first level trigger on the single muon with $p_T > 6$ GeV is foreseen [12], and the trigger efficiency can be determined using the second muon (a minor modification of the second level trigger software is required). For the operation at $L = 10^{34}$ cm^{-2} s^{-1} the single muon trigger with $p_T > 6$ GeV will have too high rate therefore two such muons will be required in the first level trigger. The trigger efficiency for this case is supposed to be known from the low luminosity run. The other option is triggering on the common dimuon track in (ρ, φ)-projection as shown schematically in Fig. 5. This allows additionally to reduce the p_T threshold and substantially increase the signal rate. This needs some extending of the ATLAS first level trigger.

Without the experimentally measurement efficiency one has to rely on the Monte Carlo calculations involving tracking of low momentum muons in the detector material and in the inhomogeneous magnetic field of the air core

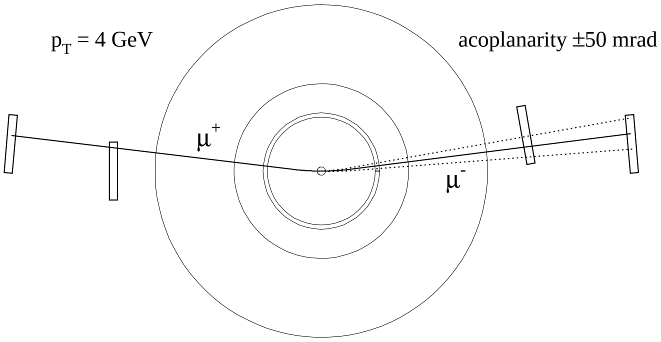

Fig. 5. The common $\mu^+\mu^-$ track in (ρ, φ)-projection (the multiple scattering is not taken into account).

toroid. In this case the accuracy of the luminosity measurement with $pp \rightarrow pp + \mu^+\mu^-$ would hardly be better than 5%.

5 Cross section estimates for LHCb

To study the potential of the method suggested for the LHCb experiment, the cross section estimates has been obtained using the particle level Monte Carlo code. The particles were tracked through some model of the LHCb detector without interaction with the material. The resolution in ϕ and θ angles was fixed by the number and the width of the strips hitted in the vertex detector. The total momentum resolution of $0.3\,p$ % was assumed [13].

The following event selection criteria were applied:

(1) Two muon tracks of opposite charges with $p_T > 1$ GeV, $E > 8$ GeV are detected;
(2) Muon pair invariant mass < 30 GeV;
(3) Difference in the measured values of muon p_T is small: $|p_T^+ - p_T^-|/(p_T^+ + p_T^-) < 0.13$.
(4) No other charged tracks are observed in the event.

The preliminary results obtained for the reference region $|\phi| < 25$ mrad are presented in Table 2. The observed multiplicity for all background sources except the two-photon one are $30 \div 60$. No events passing the condition (4) were generated, the suppression factors were roughly estimated using the fits of the multiplicity distributions for the relaxed cut (3).

Due to lower p_T threshold, the estimated LHCb signal cross section is more than 10 times larger then that for ATLAS. The statistical accuracy of 1% seems reachable at the designed luminosity of 2.10^{32} cm^{-2} s^{-1}.

By the same reason the variation of the background level in the background subtraction interval $|\phi| < 100$ mrad is bigger than for ATLAS. Some opti-

Table 2
LHCb cross section estimates for the kinematic cuts (1-3) and all cuts (the detection efficiency is not taken into account).

process	σ_{kin}, pb	σ_{all}, pb
signal	14.6	≈14.6
$\gamma\gamma$(inelastic)	0.6	0.5
Drell-Yan process	93	<0.02
Heavy quarks decays	690	<0.02
π, K decays	∼50000	<0.3
background	93.6	$0.5 \div 0.84$ (<6%)

mization of cuts might be necessary to keep the systematic error small.

6 Conclusion

The method described allows for the ATLAS offline luminosity determination using the two-photon process $pp \rightarrow pp + \mu^+\mu^-$ with the accuracy $\leq 2\%$ in the luminosity range of $10^{33} \div 10^{34}$ cm^{-2} s^{-1}. The preliminary cross section estimates done for LHCb promise the same level of the luminosity measurement accuracy at $L = 2 \cdot 10^{32}$ cm^{-2} s^{-1}.

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