LIGHT-BY-LIGHT SCATTERING CROSS-SECTION MEASUREMENTS AT THE LHC*

G.K. Krintiras

Department of Physics and Astronomy, The University of Kansas
Malott Hall, 1251 Wescoe Hall Dr., Lawrence, KS 66045, USA

I. Grabowska-Bold

Department of Physics and Applied Computer Science
AGH University of Science and Technology
Al. Mickiewicza 30, 30-059 Kraków, Poland

M. Kłusek-Gawenda

Institute of Nuclear Physics Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland

É. Chapon

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

R. Chudasama

Department of High Energy Physics, Tata Institute of Fundamental Research
Mumbai 400005, India

R. Granier de Cassagnac

Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS/IN2P3
Palaiseau, France

Received 1 August 2022, accepted 28 September 2022,
published online 14 December 2022

Light-by-light (LbyL) scattering, $\gamma\gamma \to \gamma\gamma$, is a rare Standard Model (SM) process, also proposed as a sensitive channel to study physics beyond the SM. In these proceedings, we perform a statistical combination of existing $\gamma\gamma \to \gamma\gamma$ cross section measurements at the LHC with the aim of checking the consistency with different SM predictions. Using a simplified

* Presented at the 29[th] International Conference on Ultrarelativistic Nucleus–Nucleus Collisions: Quark Matter 2022, Kraków, Poland, 4–10 April, 2022.

set of assumptions, we find the averaged result of 115 ± 19 nb, consistent with SM predictions within two standard deviations. For the first time, we also consider the contribution from the $\eta_b(1S)$ meson production to the diphoton invariant mass distribution.

DOI:10.5506/APhysPolBSupp.16.1-A123

1. Introduction

In these proceedings, we present an average of the integrated fiducial cross sections for the $\mathrm{Pb{+}Pb}\,(\gamma\gamma) \rightarrow \mathrm{Pb}^{(*)}{+}\mathrm{Pb}^{(*)}\,\gamma\gamma$ production at $\sqrt{s_{NN}} = 5.02$ TeV using the available LHC measurements from the ATLAS [1–3] and CMS [4] collaborations.

2. Measured and predicted light-by-light cross sections

In the offline ATLAS (CMS) analysis used as input measurements, events were selected with exactly two photons, each with transverse energy $E_{\mathrm{T}} > 2.5$ (>2.0) GeV and pseudorapidity $|\eta| < 2.4$ that satisfied further selection requirements described in Refs. [3, 4]. To suppress nonexclusive background, characterized by a final state with larger transverse momenta, p_{T}, and diphoton acoplanarities, $A_\phi = (1 - |\Delta\phi^{\gamma\gamma}|/\pi)$, the p_{T} and A_ϕ were required to be $p_{\mathrm{T}}^{\gamma\gamma} < 1$ GeV and $A_\phi < 0.01$, respectively, and the invariant mass of the pair to be $m_{\gamma\gamma} > 5$ GeV. The cross section for the $\mathrm{Pb} + \mathrm{Pb}\,(\gamma\gamma) \rightarrow \mathrm{Pb}^{(*)}{+}\mathrm{Pb}^{(*)}\,\gamma\gamma$ process was measured in fiducial phase-space regions, defined by the above requirements, and reflecting the selection at the reconstruction level. A summary of the available measurements along with their total uncertainty, evaluated as the quadratic sum of the individual sources, is presented in Table 1.

The theoretical predictions for the $\mathrm{Pb} + \mathrm{Pb}\,(\gamma\gamma) \rightarrow \mathrm{Pb}^{(*)}{+}\mathrm{Pb}^{(*)}\,\gamma\gamma$ production cross section at $\sqrt{s_{NN}} = 5.02$ TeV are calculated numerically at leading order (LO) in SuperChic [5]. An alternative LbyL numerical calculation is performed in Ref. [6], with the main difference of 2–4% relative to SuperChic originating from the implementation of the nonhadronic-overlap condition of the Pb ions. In either case, next-to-leading-order (NLO) QCD and QED corrections [7, 8] increase the cross section by a few percent, and are taken into account in the quoted total uncertainties of 10%. A summary of theoretical cross-section predictions with their uncertainties is shown in Table 2, separately for the phase-space regions defined in Table 1. Based on these numbers, the ratios of $77/101 \approx 0.76$ and $77/50 \approx 1.54$ are used as correction factors accounting for differences in the definition of phase-space regions between the two experiments.

Table 1. Summary of the fiducial LbyL cross-section measurements ($\sigma^{\rm fid}_{\rm raw}$) at 5.02 TeV performed by the ATLAS and CMS collaborations. When applicable, they are further scaled by correction factors ($\sigma^{\rm fid}_{\rm cor}$) to account for differences in the definition of phase-space regions, as described in the main text. Total uncertainties are shown. The symbol "—" means that no corresponding cross-section measurement currently exists. The cross sections marked with † are those used as input to the extraction of the averaged value of the Pb+Pb ($\gamma\gamma$) $\rightarrow$ Pb$^{(*)}$+Pb$^{(*)}$ $\gamma\gamma$ process.

		ATLAS		CMS	
$\sqrt{s_{NN}}$	Year (Lumi. [nb^{-1}])	$\sigma^{\rm fid}_{\rm raw}$ [nb]	$\sigma^{\rm fid}_{\rm cor}$ [nb]	$\sigma^{\rm fid}_{\rm raw}$ [nb]	$\sigma^{\rm fid}_{\rm cor}$ [nb]
5.02 TeV	2015 (0.39–0.48)	70 ± 29 [1]	108 ± 45	120 ± 55 [4]	$91 \pm 42^\dagger$
	2018 (1.73)	78 ± 15 [2]	120 ± 23	—	—
	2015+2018 (2.2)	120 ± 22 [3]	$120 \pm 22^\dagger$	—	—

Table 2. Predicted cross sections for LbyL scattering at 5.02 TeV. Uncertainties take into account derivations from alternative approaches. The cross section marked with † is used as reference.

$\sqrt{s_{NN}}$	Process	Accuracy	$\sigma^{\rm fid}_{\rm theo}$ [nb]	Phase-space region
5.02 TeV	Pb+Pb($\gamma\gamma$) $\rightarrow$ Pb$^{(*)}$+Pb$^{(*)}\gamma\gamma$	LO	101 ± 10 [5]	$E_{\rm T} > 2.0$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 5$ GeV, $p_{\rm T}{}^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
		LO	103 ± 10 [6]	$E_{\rm T} > 2.0$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 5$ GeV, $p_{\rm T}{}^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
		LO	$77 \pm 8^\dagger$ [5]	$E_{\rm T} > 2.5$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 5$ GeV, $p_{\rm T}{}^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
		LO	80 ± 8 [6]	$E_{\rm T} > 2.5$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 5$ GeV, $p_{\rm T}{}^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
		LO	50 ± 5 [5]	$E_{\rm T} > 3.0$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 6$ GeV, $p_{\rm T}{}^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
		LO	51 ± 5 [6]	$E_{\rm T} > 3.0$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 6$ GeV, $p_{\rm T}{}^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$

The background contribution of $\eta_b(1S)$ meson production to the Pb + Pb ($\gamma\gamma$) $\rightarrow$ Pb$^{(*)}$+Pb$^{(*)}$ $\gamma\gamma$ process is studied for the first time. Figure 1 shows a comparison of the theoretical calculations [6] of differential cross sections as a function of the invariant mass of the diphoton system for $\gamma\gamma \rightarrow \gamma\gamma$ scattering, typically used to set limits on particle production beyond the Standard Model, and $\eta_b(1S)$ meson production with decays into two photons in the final state. Although the height of the resonance peak is 1 nb, this contribution is therefore found to be insignificant in the context of the LbyL measurement because the experimental $m_{\gamma\gamma}$ bins are typically very wide.

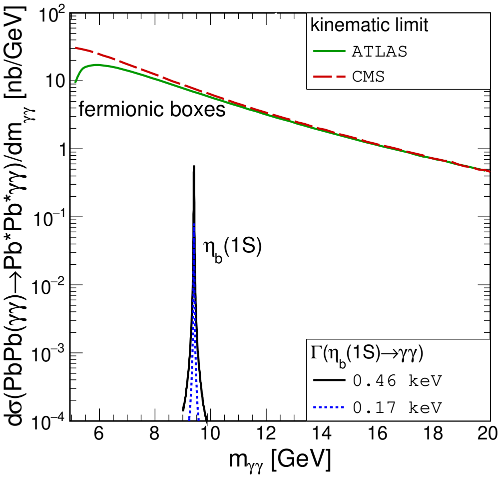

Fig. 1. Differential cross sections for the signal (contribution from fermionic boxes [6]) $\mathrm{Pb+Pb}\,(\gamma\gamma) \to \mathrm{Pb}^{(*)}\mathrm{+Pb}^{(*)}\,\gamma\gamma$ and the intermediate $\gamma\gamma \to \eta_b(1S) \to \gamma\gamma$ background production process as a function of the diphoton invariant mass. For the signal, the ATLAS and CMS kinematic requirements from Refs. [3] and [4], respectively, are adopted. For the background $\eta_b(1S)$ process, the decay to a diphoton system is shown for the maximum and minimum values of diphoton decay rates of 0.46 and 0.17 keV, respectively.

3. Averaged cross-section measurement at the LHC

The cross-section measurements, described in Section 2 and denoted by † in Table 1, are used as input to an averaged cross section. We use the best linear unbiased estimator (BLUE) method to average these measurements. Systematic uncertainties are categorized and a simplified correlation scheme is assumed [9].

The averaged cross-section measurement for the LbyL process at 5.02 TeV is

$$\begin{aligned}\sigma^{\mathrm{fid}}_{\mathrm{meas}} &= 115 \pm 15\ (\mathrm{stat.}) \pm 11\ (\mathrm{syst.}) \pm 3\ (\mathrm{lumi.}) \pm 3\ (\mathrm{theo.})\ \mathrm{nb} \\ &= 115 \pm 19\ \mathrm{nb}\,,\end{aligned}$$

with a relative uncertainty of 17%. The statistical uncertainty is still found to be the dominant overall uncertainty. Figure 2 shows a summary of the $\mathrm{Pb + Pb}\,(\gamma\gamma) \to \mathrm{Pb}^{(*)}\mathrm{+Pb}^{(*)}\,\gamma\gamma$ measurements at 5.02 TeV and their comparison to the theory predictions from Table 2. The averaged cross section is consistent within about two standard deviations with the SM predictions. A related analysis [10] has shown that the recently observed tetraquark state $X(6900)$ could, in principle, account for the excess seen in the $\mathrm{Pb + Pb}\,(\gamma\gamma) \to \mathrm{Pb}^{(*)}\mathrm{+Pb}^{(*)}\,\gamma\gamma$ data.

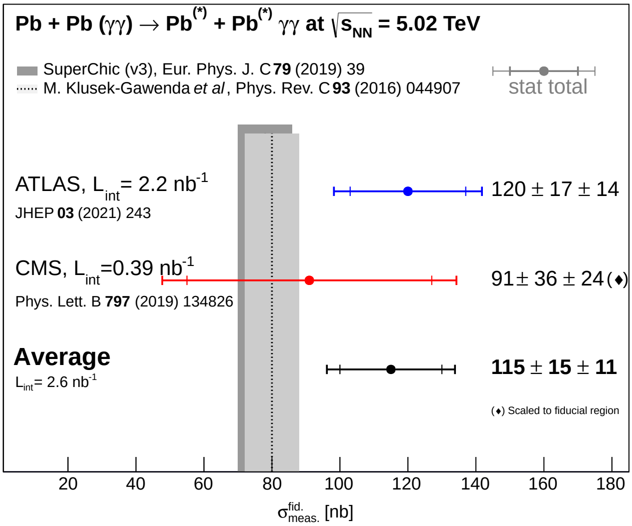

Fig. 2. The averaged Pb+Pb $(\gamma\gamma) \to \mathrm{Pb}^{(*)}+\mathrm{Pb}^{(*)}\,\gamma\gamma$ cross-section value along with the individual cross-section measurements at 5.02 TeV from ATLAS and CMS. The theoretical predictions [5, 6] are computed at LO accuracy. The $\sigma^{\mathrm{fid}}_{\mathrm{theo}}$ uncertainties used to compute Pb + Pb $(\gamma\gamma) \to \mathrm{Pb}^{(*)}+\mathrm{Pb}^{(*)}\,\gamma\gamma$ are described in the text.

4. Summary

Although an improved determination of the integrated fiducial Pb + Pb $(\gamma\gamma) \to \mathrm{Pb}^{(*)}+\mathrm{Pb}^{(*)}\,\gamma\gamma$ cross section by approximately 10% could be potentially achieved relative to current measurements, further improvements are expected with the inclusion of existing or forthcoming LHC nuclear data.

This article is part of a project that has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 824093, better known as STRONG-2020. G.K.K. is supported by the Office of Nuclear Physics in the Department of Energy (DOE NP) under grant number DE-FG02-96ER40981. I.G.B. is supported by the National Science Centre, Poland (NCN) under grant number UMO-2020/37/B/ST2/01043 and by PL-GRID infrastructure.

REFERENCES

[1] ATLAS Collaboration, *Nature Phys.* **13**, 852 (2017).
[2] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. Lett.* **123**, 052001 (2019).

[3] ATLAS Collaboration (G. Aad *et al.*), *J. High Energy Phys.* **2103**, 243 (2021).

[4] CMS Collaboration, *Phys. Lett. B* **797**, 134826 (2019).

[5] L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, *Eur. Phys. J. C* **79**, 39 (2019).

[6] M. Kłusek-Gawenda, P. Lebiedowicz, A. Szczurek, *Phys. Rev. C* **93**, 044907 (2016).

[7] Z. Bern *et al.*, *J. High Energy Phys.* **0111**, 031 (2001).

[8] M. Kłusek-Gawenda, W. Schäfer, A. Szczurek, *Phys. Lett. B* **761**, 399 (2016).

[9] G.K. Krintiras *et al.*, arXiv:2204.02845 [hep-ph].

[10] V. Biloshytskyi *et al.*, arXiv:2207.13623 [hep-ph].