CERN Student Project Report

Measurement of J/ψ photoproduction in UPC of PbPb at 5 TeV

Vasyl Dobishuk
Supervisors: Burkhard Schmidt, Daniel Johnson

Geneva, Switzerland

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1 Introduction

This note gives a brief description of J/ψ photoproduction in ultra-peripheral collisions (UPC) of relativistic PbPb ions at a center-of-mass energy of 5 TeV with the LHCb experiment.

UPCs of two nuclei involve electromagnetic interactions, two-photon or photonuclear, but not hadronic, at impact parameters larger than the sum of their radii. The large cross-section for photon-nucleus reactions dependents on a high virtual photon flux that is proportional to Z^2, where Z is the charge of the nucleus ($2 \cdot 6700$ in cross-section for PbPb). Because of large impact parameter, the final state multiplicity is very small and, in fact, the events can be fully reconstructed into detector acceptance. Hence, these features greatly simplify detection and make experimental attractiveness of studying of such photon-induced reactions.

The most common final state among photonuclear interactions is a vector meson. This can be explained by the photon quantum numbers $J^{PC} = 1^{--}$, since the photon, emitted from the electromagnetic field of one of the projectiles, at first fluctuates to a $q\bar{q}$-pair, which then scatters elastically from the other projectile through pomeron exchange. For heavy ions, the amplitudes for scattering from individual nucleons add coherently when the 4-momentum transfer q is small ($|q| < \frac{\hbar c}{R_A}$). Such coherent photoproduced J/ψ mesons are the subject of study of this analysis.

The main interests in photoproduction at LHC is derived from the possibility of a direct determination of the gluon distribution (PDF) in nucleons and nuclei, a probe of QCD, investigation of pomeron nature, gluon saturation effects at low Bjorken-x (fraction of the proton momentum carried by the gluon up to 10^{-6}).

The comprehensive review of UPCs is described in [1, 2]. The more LHCb-specific review of such collisions is [3].

The LHCb detector [4, 5] is a single-arm forward spectrometer, suitable for studying of UPCs as its tracking, calorimetry and particle identifications are in the pseudorapidity acceptance $2 < \eta < 4.5$. In addition, LHCb triggers are constructed to trigger on events with low particle transverse momentum.

2 Project results

2.1 Data and Monte Carlo sets

The analysed data sample is a PbPb data, collected by the LHCb Collaboration in November and December 2015, with the nucleon-nucleon centre-of-mass energy of 5 TeV. The data were taken when only a minimum bias trigger was activated. About two thirds of data taking was beam-gas (PbAr) collisions [6]. The different collision configurations have complicated calculation of integrated luminosity, that at present have large uncertainty ($10 - 20\,\%$).

The STARlight event generator [7] is a MC simulation program for UPCs of relativistic ions, focusing on LHC and RHIC energies to produce: vector mesons states (in photonuclear interactions) and lepton or meson pairs, or single mesons (two-photon interactions).

The numerous MC samples were generated on generator level:

1. 1M coherent and incoherent photoproduced J/ψ mesons: $\gamma A \to (J/\psi \to \mu^+\mu^-)A$;

2. 1M 2-photon reactions $\gamma\gamma \to \mu^+\mu^-$.

2.2 Event selection

The selection of coherently photoproduced J/ψ mesons from PbPb datasets is based on the low multiplicity of final state. In experiment we expect the presence of only two long tracks in the LHCb acceptance, both reconstructed as muons with isMuon algorithm. Consequently, events with precisely two muons, which can come from photonuclear vector meson production, are selected. In order to reduce signal contamination from hadronic reactions we required that there are no Downstream, Upstream, TT tracks and no photon, i.e., no other reconstructed particles in the spectrometer. Therewith we accept some activity in VELO tracker, since there are no any certain limits for the number of VELO tracks.

L0MUON	
muon p_T	> 360 MeV/c
Hlt1BBMicroBiasVelo	
Passed L0SPD | L0CALO | L0MUON	
nVeloTracks	$>= 1$
Hlt2BBPassThrough	

Table 1: Important trigger lines and their requirements for the given analysis.

The minimal demands were requested on the trigger level for the present analysis. Each of selected events should be triggered at L0 by L0MUON and at Hlt1 by Hlt1BBMicroBiasVelo, while at Hlt2 it passes through without any decision. The crucial trigger lines and their requirements are summarized in Table 1.

The hardware trigger L0MUON line requires a single muon track with the transverse momentum $p_T > 360\,\mathrm{MeV}/c$. The software trigger Hlt1BBMicroBiasVelo line, based on L0 decision, requires at least one VELO track.

The full list of selection cuts applied for this analysis are sum up in Table 2.

Variable	Value
BCType (type of collisions)	$= 3$
nSPDhits	< 20
muon track χ^2/ndf	< 3
mass window	$< 300\,\mathrm{MeV/c^2}$
muon track ghost probability	< 0.3
muon p_T	$> 750\,\mathrm{MeV/c}$
isMuon (muon identification)	$= 1$
nLongTracks	$= 2$
nDownstreamTracks	$= 0$
nUpstreamTracks	$= 0$
nTTracks	$= 0$

Table 2: Total offline selection criteria.

Coherent J/ψ candidates are selected by requiring two muons to have transverse momentum $p_T > 750\,\mathrm{MeV}/c$, and total event charge particle multiplicity, detected by a scintillating pad detector (SPD), to be less than 20. Also both muons have to be in the pseudorapidity range $2 < \eta < 4.5$ and have invariant mass within $40\,\mathrm{MeV}/c^2$ of PDG J/ψ mass value ($\mathrm{M}\left(J/\psi(1S)\right) = 3096.916 \pm 0.011\,\mathrm{MeV}/c^2$ [8]).

Since about two thirds of the data include information from beam-gas interactions (PbAr collisions), the bunch-crossing type (BSType) "Beam-Beam" was requested to select PbPb collisions. Nevertheless the contribution from residual PbAr interactions can be still presented in PbPb data [6].

2.3 Analysis technique

The analysis strategy for the present work can be summarized in such plan:

1. Decay channel: $J/\psi \to \mu^+\mu^-$ with branching fraction $\mathcal{B}(J/\psi(1S) \to \mu^+\mu^-) = (5.961 \pm 0.033)\%$ [8].

2. The differential cross-section of coherent photoproduction of J/ψ mesons:

$$\frac{d\sigma^{coh}}{dy} = \frac{N}{\Delta y \cdot \epsilon_{tot} \cdot \mathcal{L}}$$

- σ: cross-section times branching fraction for J/ψ to decay to dimuon, which within $2 < \eta < 4.5$;
- N: number of J/ψ mesons in a single rapidity bin;
- Δy: the width of a single rapidity bin;
- ϵ_{tot}: total efficiency;

$$\epsilon_{tot} = \epsilon_{acc} \cdot \epsilon_{track} \cdot \epsilon_{muon} \cdot \epsilon_{trig}$$

- $\mathcal{L}$: integrated luminosity;

2.4 Signal extraction

The strategy to obtain the total number of coherent photoproduced J/ψ mesons in present analysis is based on procedure of two stage fit. Each steps of it are described below.

Analysis of invariant mass spectrum – isolation of continuum

The main aim of this step is to compute continuum yield in J/ψ mass window that is for our analysis within $40\,\mathrm{MeV/c^2}$ of PDG J/ψ meson mass.

The very clear invariant mass distribution of dimuon pairs is shown in Fig.1 within range $|\mathrm{M}_{\mathrm{J}/\psi,\,\mathrm{PDG}} - \mathrm{M}_{\mu\mu}| < 300\,\mathrm{MeV}/c^2$. The signal peak that corresponds to J/ψ mesons, decaying through the channel $J/\psi \to \mu^+\mu^-$, and underlying continuum muon pairs, originated from the channel $\gamma\gamma \to \mu^+\mu^-$, represent data spectrum. The sum of gaussian to describe signal, and exponential function to describe non-resonant background is used to fit it. All model parameters could be varied during the fitting. As the result, mean value for J/ψ mass and FWHM are $3097.2 \pm 0.4\,\mathrm{MeV}/c^2$ and $29.94 \pm 0.82\,\mathrm{MeV}/c^2$ respectively. The fractions of fit model components as well as the raw yields in J/ψ mass window, we obtained, are arranged in Table 3.

	f_i	N
Total	0.740	1150
Signal	0.998	1090
Continuum	0.130	60

Table 3: The relative parts of fit components of J/ψ invariant mass and the raw yields, corresponding to them within $40\,\mathrm{MeV/c^2}$ of PDG J/ψ mass.

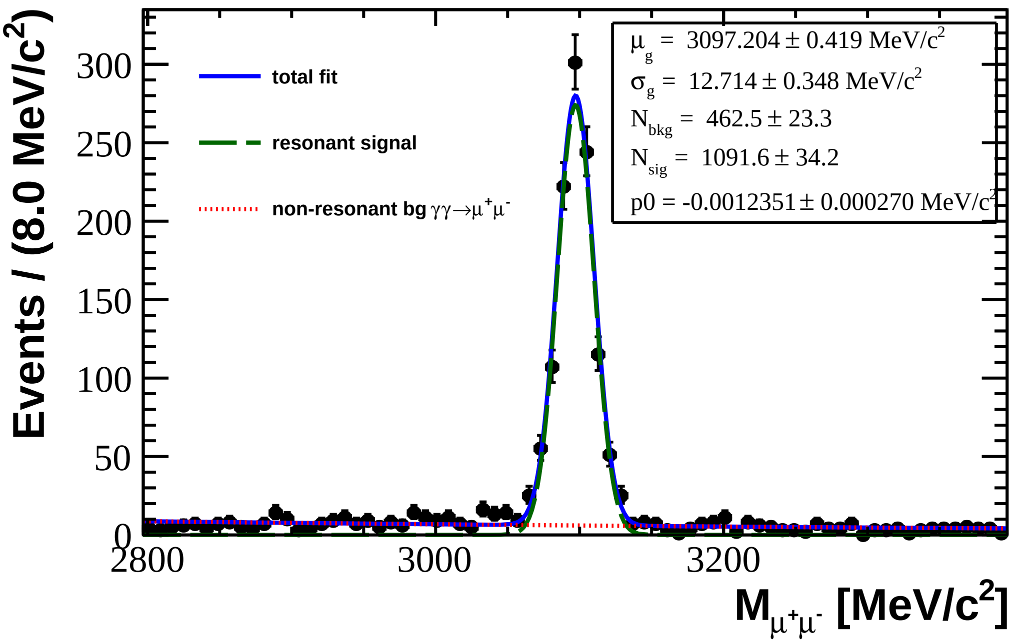

Figure 1: Invariant mass distribution of J/ψ candidates for ultra-peripheral PbPb collisions at $\sqrt{s_{NN}} = 5\,\text{TeV}$ in rapidity region $2 < Y_{J/\psi} < 4.5$ for events that passed the selection criteria.

Analysis of transverse momentum squared distribution – isolation of incoherent and hadronic backgrounds

The main aim of this step is to compute from the p_T^2 fit yield of coherent photoproduced J/ψ mesons in J/ψ mass window mentioned above.

Coherent J/ψ has a very low transverse momentum ($<p_T>= 60\,\text{MeV}/c$) due to small photon transverse momentum [1]. Hence, that gives us possibility to distinguish such mesons in p_T^2 distribution easily. Besides coherent J/ψ, under resonant peak we observe contribution from incoherent J/ψ , pure electromagnetic muon pair as well as hadronic productions. To consider these processes in p_T^2 distribution we used three STARlight MC templates (generator level) for events with two muons in the pseudorapidity range $2 < \eta < 4.5$ and J/ψ candidates in rapidity range $2 < Y_{J/\psi} < 4.5$:

1. Coherent photonuclear J/ψ meson production (PROD_MODE = 2).

2. Incoherent photonuclear J/psi meson production (PROD_MODE = 4).

3. Two-photon $\mu^+\mu^-$ pair production (PROD_MODE = 1), –

and one exponential functions to describe contribution of hadronic J/ψ.

Prior to the fit all MC models were smeared using smearing factors regarding the value of muon momentum to mimic detector response. As the result, each of momentum components was corrected in the next way:

$$p_i^{smeared} = p_i(1 + s^{res} \cdot r),$$

where p_i – i component of muon momentum, s^{res} – a relevant smearing factor for muon momentum, r – random value distributed by the gaussian with a mean value equals 0 and standard deviation equal 1. The arrays of smearing factors and muon momentum are [0.011, 0.0085, 0.010, 0.011, 0.011, 0.010, 0.013, 0.014] and [0, 20, 40, 60, 80, 100, 120, 160, 1000] in GeV/c respectively [].

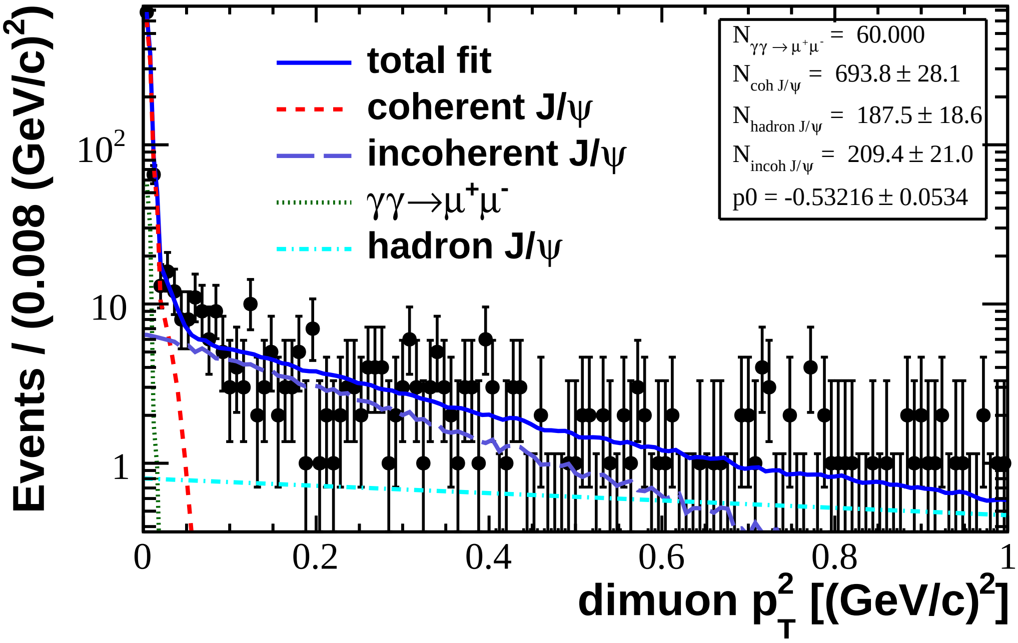

Figure 2: Dimuon p_T^2 distribution for ultra-peripheral PbPb collisions at $\sqrt{s_{NN}} = 5\,\text{TeV}$ in rapidity region $2 < y_{J/\psi} < 4.5$ and invariant mass window $|M_{J/\psi,PDG} - M_{\mu\mu}| < 40\,\text{MeV}/c^2$ for events that passed the selection criteria. The points representing the data are fitted with the composite model (blue solid) consisting of three STARlight MC templates such as coherent (red short dashed), incoherent (violet long dashed) J/ψ, pure electromagnetic dimuon productions (green dotted) and exponential function for hadronic J/ψ component (light-blue dotted-dashed).

The characteristic peak at very low p_T^2 on the Fig.2 is formed chiefly by coherent J/ψ as the yield of signal-like two photon contribution is restricted to the value received from the invariant mass fit. The long shoulder in the p_T^2 spectrum, up to $10\,(\text{GeV}/c^2)^2$, caused by hadronic production.

The relative normalisation for coherent, incoherent and hadronic J/ψ was left float. By fitting in two different ranges such as $[0;10]$ $(\text{GeV}/c^2)^2$ and $[0;1]$ $(\text{GeV}/c^2)^2$ we obtained stable raw yield for simulated processes in the range between 0 and 1 $(\text{GeV}/c^2)^2$ (Table 4), while for hadronic component the fit is unstable in this range.

	Fit range $[0;10]$, $(\mathrm{GeV}/c)^2$		Fit range $[0;1]$, $(\mathrm{GeV}/c)^2$	
Integrated range $[0;1]$, $(\mathrm{GeV}/c)^2$	f_i	N	f_i	N
Total	0.901	1037	0.932	967
Coherent	1	694	1	694
Incoherent	0.981	205	0.981	205
$\gamma\gamma \to \mu^+\mu^-$	1	60	1	60
Hadronic	0.415	78	0.1	8
Integrated range $[1;10]$, $(\mathrm{GeV}/c)^2$	f_i	N	f_i	N
Total	0.099	114	0.068	71
Coherent	0	0	0	0
Incoherent	0.019	4	0.019	4
$\gamma\gamma \to \mu^+\mu^-$	0	0	0	0
Hadronic	0.585	110	0.9	67

Table 4: The relative parts of fit components of dimuon tranverse momentum squared spectrum and the raw yields corresponding to them for the J/ψ candidates within $40\,\mathrm{MeV}/c^2$ of PDG J/ψ mass.

3 Conclusions

In summary, the first measurements of coherent J/ψ photoproduction in a low multiplicity data sample of ultra-peripheral PbPb collisions at 5 TeV in rapidity region between 2 and 4.5 at LHCb is presented. The new signal extraction method of two stage fit with comparison to that proposed by ALICE [9, 10] is applied. An investigation of the square of J/ψ tranverse momentum distribution for the events within J/ψ mass window revealed that background contains also a major hadronic component, except dimuon continuum. Such hadronic J/ψ are dominated in the region $p_T^2 > 1\,\mathrm{GeV}/c^2$, where coherent and incoherent J/ψ bulk is minor. Fitting of p_T^2 specturm in different ranges showed the stable results for all fit constituents, excluding hadronic. As the result, the raw yield of coherent photoproduced J/ψ mesons was calculated by optimizing fit model to our datasets.

Further improvements of fit model are needed to describe properly the long tail of p_T^2 distribution. Also it is necessary to check the probable contribution of J/ψ from $\psi(2S)$.

4 Future plans

This project work is a good start point for the complete analysis of coherent J/ψ photoproduction in PbPb collisions at 5 TeV at LHCb. Therefore our plans to prepare a draft of the Analysis note.

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