Title
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Photoproduction at RHIC and the LHC

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The strong electromagnetic fields carried by relativistic highly charged ions make heavy-ion colliders attractive places to study photonuclear interactions and two-photon interactions. At RHIC, three experiments have studied coherent photoproduction of ρ^0, 4π, J/ψ, e^+e^- pairs, and e^+e^- pairs where the electron is bound to one of the incident nuclei. These results show that photoproduction studies are possible, and demonstrate some of the unique possibilities due to the symmetric final states and the ion targets. The LHC will reach photon-nucleon energies many times higher than at HERA; these collisions can be used to measure the gluon distributions in nuclei at very low Bjorken$-x$, where shadowing and gluon saturation may become important; LHC $\gamma\gamma$ collisions may also be attractive places to search for some types of new physics. ATLAS, CMS and ALICE are all planning to study photoproduction. After introducing the principles of photoproduction at hadron colliders, I will review recent results from RHIC on meson and e^+e^- production, and then discuss prospects for studies at the LHC.

I. INTRODUCTION

Photoproduction has traditionally been studied with photon beams at fixed target accelerators and in *ep* collisions at HERA. However, photoproduction may also be studied at hadron colliders; the photons come from the electromagnetic fields accompanying relativistic nuclei [1]. The photon flux scales as the nuclear charge, Z, squared, so heavy nuclei generate intense fields. Both photonuclear and 'two-photon' interaction can be studied. These are known as 'ultra-peripheral collisions,' or UPCs.

The maximum photon energy from a nucleus with radius R_A and Lorentz boost γ is $\gamma\hbar c/R_A$, or, for heavy ions about 3 GeV with RHIC and 100 GeV at the LHC. This corresponds to γp center of mass energies of 25 and 800 GeV respectively. Light ions can reach considerably higher energies; the latter is four times higher than is available at HERA. Until a new *ep* collider, is built, the LHC will provide the highest energy photon-nucleon and two-photon collisions in the world.

Besides the higher energies, heavy ion colliders have other advantages. Their electromagnetic fields are intense enough so that three and four photon interactions can be observed, so one can study multiple interactions involving a single ion pair. Relativistic heavy-ions are highly charged, so the resulting electromagnetic fields are very strong. The common impact parameter leads to correlations in photon energy and linear polarization. So far, three and four photon reactions have been studied at RHIC. Bound-free pair production (BFPP) is another unique reaction. In it, an e^+e^- pair is produced with the electron bound to one of the incident nuclei. This process produces a beam of single-electron ions; at the LHC this beam may carry enough power to quench superconducting magnets, limiting the achievable luminosity.

After reviewing current results, this writeup will discuss the future physics possibilities at the LHC.

II. RESULTS FROM RHIC AND THE TEVATRON

The first study of photoproduction at hadron colliders was a measurement of two photon production of $\mu^+\mu^-$ pairs at the CERN Intersecting Storage Rings (ISR) *pp* collider [2]. In the 1980s, e^+e^- production was studied at fixed target accelerators. More recently, UPCs have been studied at RHIC at Brookhaven National Laboratory and the Fermilab Tevatron. At RHIC, the STAR and PHENIX experiments have studied a number of leptonic and hadronic final states, and a 3rd experimental collaboration has measured BFPP with copper beams [3].

The pioneering STAR studies of ρ^0 photoproduction and decay to $\pi^+\pi^-$ established the basic experimental parameters for UPCs. For this, STAR used a trigger based on slats of scintillator surrounding a central detector to select

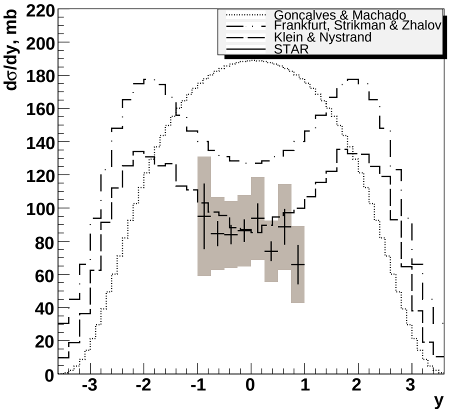

FIG. 1: STAR measurement of $d\sigma/dy$ for ρ^0 photoproduction, compared with three theoretical models [8]. The Goncalves and Machado calculation is based on a saturation model, while the other two models are based on Glauber calculations.

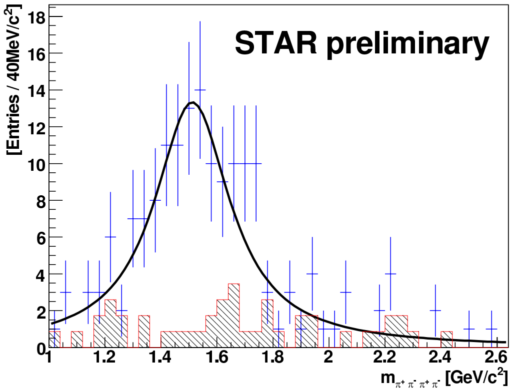

FIG. 2: Invariant mass for coherently photoproduced four-pion final states from the STAR 2004 run [9]. The points with error bars are net charge 0 ($\pi^+\pi^-\pi^+\pi^-$), while the shaded histogram is a background estimate from the net charge 2 ($\pi^+\pi^+\pi^+\pi^- + \pi^+\pi^-\pi^-\pi^-$) data.

events with low muliplicity. The slat hits were required to be roughly back-to-back transversely, as expected from π^+ and π^- produced in the decay of a low p_T ρ^0. The initial analysis selected events with ρ^0 $p_T < 150$ MeV/c, as is expected in coherent photoproduction [4]. Like-sign pion pairs ($\pi^+\pi^+ + \pi^-\pi^-$) were a measure of the background.

STAR found that the coherent production cross-section agreed with theoretical calculations based on the Weiszacker-Williams photon flux, convoluted with photoproduction cross-sections determined by using a Glauber calculation [7]. The calculations used HERA data on $\gamma p \rightarrow \rho^0 p$ as input. Figure 1 compares the ρ^0 rapidity distribution with three calculations, including two based on Glauber models. STAR also observed direct $\pi^+\pi^-$ photoproduction (without the ρ^0 intermediary), through it's interference with $\rho^0 \rightarrow \pi^+\pi^-$. Later STAR studies of ρ^0 photoproduction expanded to include incoherent photoproduction (where the photon scatters from a single nucleon, and the final state ρ^0 has higher p_T) [8], and also observed ρ^0 photoproduction in dA collisions.

STAR also studied ρ^0 photoproduction accompanied by mutual Coulomb excitation, whereby the two nuclei are electromagnetically excited. This reaction occurs primarily by three-photon exchange - one for each nuclear excitation, plus a third to produce the ρ^0. The two neutrons produced by the nuclear deexcitation make a simple and convenient experimental trigger; these results have smaller systematic errors than the corresponding exclusive ρ^0 results. The photons act independently, but, their common impact parameter introduces correlations [5]. The mutual Coulomb excitation 'tag' events with smaller average impact parameters, and consequently, a harder photon spectrum [6].

More recently, STAR has studied the photproduction of four-pion final states. They are expected to be produced primarily through excited ρ states, most notably the $\rho^0(1450)$ and/or the $\rho^0(1700)$. STAR observes a broad peak with a mass of roughly 1500 MeV/c^2, and a width of a few hundred MeV/c^2 [9]; the yield is a small fraction of the ρ^0. Figure 2 shows the 4π invariant mass distribution; this distribution is compatible with earlier photoproduction studies.

One unique aspect of UPC photoproduction is due to the initial state symmetry. Photoproduction can occur through two indistinguishable channels: either nucleus #1 (*e.g. from the blue beam*) can emit a photon which scatters from nucleus #2 (*e.g. from the yellow beam*), or nucleus #2 emits a photon which scatters from nucleus #1. These two possibilities are indistinguishable, and are related by a parity transformation. Because vector mesons are negative parity, the two amplitudes interfere destructively, and, at mid-rapidity, where the two amplitudes A are the same, the cross-section is [10, 11]

$$\sigma(b, y=0) = |A(b, y=0)|^2 \left[1 - cos(\vec{p_T}\cdot\vec{b})\right] \tag{1}$$

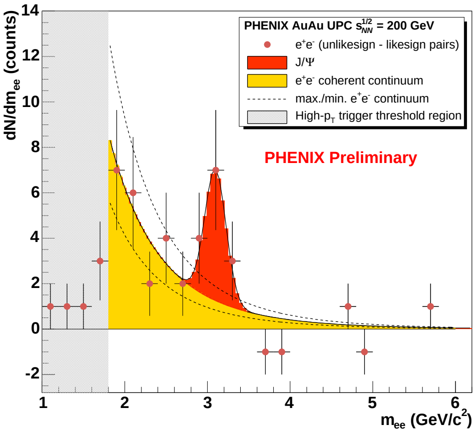

FIG. 3: PHENIX measurements of coherent e^+e^- production. The yellow shading shows the expectation from contiuum (electromagnetic) e^+e^- production, while the red Gaussian shows the J/ψ decay to e^+e^- [15].

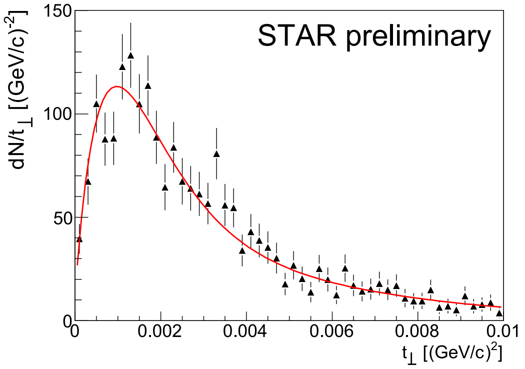

FIG. 4: The $t_\perp = p_T^2$ spectrum for ρ^0 photoproduction accompanied by mutual Coulomb excitation in STAR, for $0.1 < |y| < 0.5$ [12].

where $\vec{b}$ is the impact parameter vector. This interference suppresses production at low p_T. Fig. 4 shows the $t_\perp = p_T^2$ spectrum for ρ^0 photoproduction with $0.1 < |y| < 0.5$; the downturn for $t_\perp < 0.001$ GeV^2 is due to the interference [12].

STAR has also studied purely electromagnetic production of e^+e^- pairs [13], again acompanied by mutual Coulomb excitation. Because of the low p_T of the individual leptons, the neutrons from the Coulomb excitation were necessary for triggering. Although this process is often described as 'two-photon' production, a recent theoretical calculation finds that higher order corrections are required to describe the data [14].

PHENIX has focused on higher mass final states, using a calorimetric electron trigger. Figure 3 shows the mass spectrum of coherently produced e^+e^- final states [15]. Electromagnetic e^+e^- production is seen at a rate consistent with that expected for 'two-photon' production. Above it, a J/ψ peak is observed, containing 10 ± 3 events.

CDF has recently published a 16-event mass spectrum for exclusive e^+e^- production in 1.8 TeV $\overline{p}p$ collisions at the Fermilab Tevatron[16]. A more recent CDF study of $\mu^+\mu^-$ production found 334 events, including continuum $\mu^+\mu^-$, $J/\psi \rightarrow \mu^+\mu^-$ and $\psi' \rightarrow \mu^+\mu^-$ [17]. For protons, one background to J/ψ photoproduction is from double-Pomeron production of χ_c, followed by $\chi_c \rightarrow J/\psi\gamma$, with the low energy photon escaping the detector.

Another important UPC reaction is bound-free pair production (BFPP) where an e^+e^- pair is produced with the electron bound to one of the incident ions, leaving a single-electron atom [18]. Since charge, but little momentum is transferred to the atom, BFPP produces a well collimated beam of ions, with increased magnetic rigidity. With lead beams at the LHC, the BFPP cross-section is about 280 barns; the resulting beam of single-electron lead will strike the beampipe about 380 m downstream from the interaction region. At full LHC luminosity, this beam carries about 25 W of power, potentially enough to quench the target superconducting dipole magnet [19]. BFPP was recently measured with copper beams at RHIC. Showers from single-electron copper ions striking the RHIC beampipe were observed about 140 m downstream from the interaction point, at a rate consistent with the expected 0.2 b cross-section [3].

III. PLANS FOR THE LHC

The prospects for studying high-energy photoproduction with UPCs at the LHC has attracted considerable recent attention [20]. UPCs can be used to probe many aspects of physics. Here, we focus on three topics.

Considerable attention has been paid to measurements of the parton (particularly gluons) distribution functions of nuclei. Several approaches are under consideration. Experimentally, the simplest final state is heavy quarkonium, the J/ψ or the Υ. Photoproduction of a vector meson with mass m_V occurs when a photon with energy k interacts with a gluon with momentum fraction $x = m_V^2/4km_p$ and virtuality $Q^2 = (M_V/2)^2$; k depends on the rapidity of the vector meson: $k = m_V/2exp(\pm y)$. Of course, a second, soft gluon is required to conserve momentum and color charge.

The two-fold ambiguity in k is due to the unknown photon direction; it disappears at $y = 0$, and may be resolved elsewhere by comparing photoproduction with and without nuclear breakup. With this, vector meson photoproduction can probe x values from 10^{-2} down to 10^{-5}. Other channels of interest include heavy quark photoproduction (possibly including the top) [21] and studies of γ-jet and two-jet photoproduction [22].

Another physics topics of interest is the study of the 'black disk' regime of QCD. This occurs at high enough photon energies so that one probes low enough x and Q^2 values so that one reaches the unitarity limit and the target nucleus is essentially black. In this regime, new phenomena appear. The regime is best illustrated by treating photons as $q\overline{q}$ dipoles, with varying sizes. In this regime, dipoles with smaller and smaller sizes interact. These small sizes correspond to higher masses, so high-mass diffraction is greatly enhanced.

Finally, UPCs are sensitive to some types of new physics. In particular, two-photon production of the Higgs is of great interest. Unfortunately, the cross-sections are small, but, using protons beams, with forward detectors to tag the scattered protons, it may be possible to see a signal; although unlikely to be a discovery channel, this approach will be important in characterizing the Higgs. Searches for other new phenomena, such as magnetic monopoles are also of great interest.

The ALICE, ATLAS and CMS collaborations are all planning UPC programs. These programs are largely focused on photoproduction of J/ψ, ψ' and Υ, because of the relative experimental feasibility and the physics interest. For all three detectors, triggering is the key issue; dilepton decays of heavy quarks offer relatively simple triggering. A secondary challenge, particularly for ATLAS, is being able to reconstruct charged particle tracks down to sufficiently low p_T. There is also interest in ALICE to study e^+e^- pair production using the inner silicon detector. The cross-sections are large enough that a trigger is apparently not needed [20].

IV. CONCLUSIONS

Ultra-peripheral collisions have developed greatly since the first studies of e^+e^- and $\mu^+\mu^-$ production at the ISR and fixed-target ion accelerators. Work at RHIC has proved the feasibility of a variety of measurements and shown the value of the colliding beams geometry for unique measurements.

At the LHC, the three large experiments are planning a significant program, with measurements of heavy-quarkonium production at the most advanced stage; this should lead to a rapid measurement of the gluon distributions in nuclei at low$-x$ and moderate Q^2. Later studies will look at a variety of other final states, including additioanl measurements of gluon structure functions and studies of parton saturation, and searches for new physics.

Acknowledgments

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