Photoproduction at Hadron Colliders

Spencer R. Klein, for the STAR Collaboration

Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA

Abstract.
Photoproduction can be studied at hadron colliders by using the virtual photons associated with the hadron beams. The LHC will reach photonucleon energies 10 times higher than that available elsewhere. These reactions are already being studied at RHIC. After introducing photoproduction at hadron colliders, I will discuss recent results from STAR on ρ^0, $\pi^+\pi^-\pi^+\pi^-$ and e^+e^- production.

Keywords: photoproduction, ρ^0, ultra-peripheral collisions
PACS: 13.60.Le, 25.20.Lj, 12.20.-m

INTRODUCTION

The upcoming Large Hadron Collider (LHC) will reach proton-proton energies an order of magnitude higher than any existing accelerator. Because relativistic protons and heavier nuclei accompanied by fields of virtual photons, the LHC can be used to study photonuclear and two-photon interactions at energies far beyond those accessible at HERA or other accelerators.

Photoproduction is of interest in both pp and heavy-ion collisions. Proton-proton collisions produce photons with the highest energies, and, because of the very high pp luminosities, good rates. However, for many channels, the signal to noise ratio may be lower than in ion collisions. Heavy ions are accompanied by very high photon fluxes, and, because of the very strong fields, a single ion-ion collision can induce multiple electromagnetic interactions. The correlations between the multiple photons lead to the ability to "tune" the photon beam, by selecting different photon energy spectra and polarizations. Since these reactions take place at large impact parameters, where no hadronic interactions occur, they are often known as "ultra-peripheral collisions" (UPCs).

UPCs can be used to study a variety of topics [1][2][3]. Low$-x$ gluon distributions can be probed via heavy quark (including quarkonium) and jet production. UPCs can be used for many other studies of QCD. At the LHC, photonuclear interactions can be used to search for new physics. The strong fields allow for many tests of quantum electrodynamics in the very strong field regime, where perturbation theory may be expected to fail. Many of these topics are already being studied at RHIC.

PHOTOPRODUCTION AT HADRON COLLIDERS

For most reactions, the photon flux from protons or nuclei is well described by the Weizsäcker-Williams method of virtual photons. The photon flux per unit area for an energy ω at a distance b from a relativistic nucleus with charge Z is [4]

$$N(\omega, b) = \frac{Z^2 \alpha \omega^2}{\pi^2 \gamma^2 \hbar^2} K_1^2(x) \tag{1}$$

where $x = \omega b/\gamma$, γ is the Lorentz boost of the nucleus, $\alpha \approx 1/137$ is the fine structure constant, and K_1 is a modified Bessel function. The total photon flux from an ion with radius R_A is

$$n(\omega) = \int d^2 b N(\omega, b). \tag{2}$$

The constrant $b > R_A$ is usually imposed to eliminate the photon flux inside the nucleus (where Eq. 1 fails, and, in any case, most of the flux is not usable). For photonuclear or two-photon interactions to be visible, the two nuclei must not interact hadronically, requiring $b > 2R_A$. This flux is calculated numerically, but can be approximated within about 15% by requiring $b > 2R_A$ in Eq. 2 [1].

The cross section for photonuclear interactions can be written [6]

$$\sigma(A + A \rightarrow A + A + X) = \int d^2 b P(b) \tag{3}$$

where $P(b)$ is the probability for a photonuclear interaction, $P(b) = \int d\omega N(\omega, b)\sigma_{\gamma A}(\omega)$ where $\sigma_{\gamma A}(\omega)$ is the cross section for the photonuclear interaction in question. This formulation is easy to generalize to include multiple interactions between a single ion pair:

$$\sigma(A + A \rightarrow X_1 + X_2 + \ldots) = \int d^2 P_1(b) P_2(b). \tag{4}$$

In general, $P(b) \approx 1/b^2$, so the integrand for a $n-$photon reaction goes as $1/b^{2n}$ and the more photons involved in a reaction, the smaller the average impact parameters [5]. For example, with gold at RHIC, the median impact parameter drops from 46 fm for unselected ρ^0 production to 18 fm for ρ^0 accompanied by mutual Coulomb excitation [6]. The smaller impact parameters harden the photon spectrum, from $1/\omega$ to independent of ω. For some reactions, $P(2R_A) > 1$; in this case $P(b)$ is the mean number of reaction at that b.

Factorization can be used to simplify triggering on UPCs. One reaction can serve as a 'trigger' for another. STAR has studied the reactions $Au + Au \rightarrow Au^* + Au^* + \rho^0$ and $Au + Au \rightarrow Au^* + Au^* + e^+e^-$, using signals from the neutrons emitted in the Au^* decays to trigger the detector, providing ρ^0 and e^+e^- samples without trigger bias.

The photon polarizations are also correlated. The electric field of the photon-emitting nucleus parallels the impact parameter vector, so photons are linearly polarized along the impact parameter vector. For multiple interactions between a single ion-pair, the parallel polarizations can lead to observable angular correlations between decay products [5].

RESULTS FROM STAR AT RHIC

The STAR collaboration has produced final results on ρ^0 production [7] and on two-photon production of e^+e^- pairs [8]. Events were selected with two types of triggers:

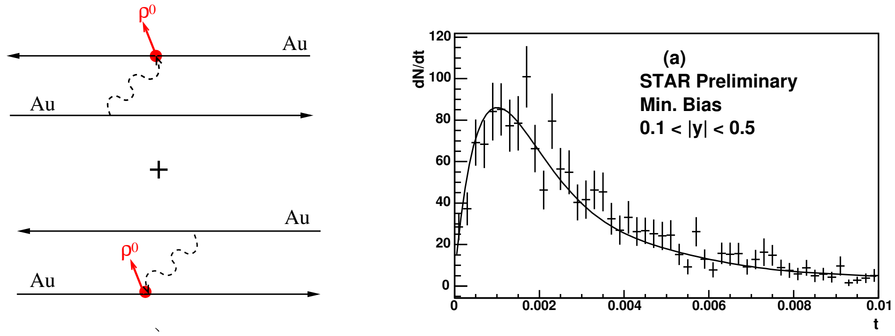

FIGURE 1. (a) Diagrams for the two interferening production mechanisms, at two spatially separated locations. (b) $t_\perp = p_T^2$ spectrum for ρ^0 accompanied by mutual Coulomb excitation. The drop at low $t_\perp$ is due to interference. The solid histogram is a fit to the data, using a model that includes the interference.

minimum bias triggers that select events with mutual Coulomb dissociation, taking advantage of factorization, and topological triggers, that select low multiplicity events with appropriate topologies in the central detector [7].

The ρ data is well described by the soft Pomeron model, and the previously discussed factorization holds. In the soft Pomeron model, the incident photon fluctuates to a quark-antiquark pair, which then elastically scatters (via Pomeron exchange) from the target nucleus [9]. Because the scattering is coherent, the momentum transfer is limited to order $\hbar/R_A$. This low p_T is a distinctive experimental signature; for gold, most of the signal occurs for $p_T < 150$ MeV/c.

Figure 1 shows the $t_\perp = p_T^2$ spectrum of ρ^0 with rapidity $0.1 < |\eta| < 0.6$, selected with stringent cuts to minimize the background [12]. At moderate and high t, the spectrum is well fit by an exponential, $dN/dt = a\exp(-bt)$. However, for $t < 0.0015\mathrm{GeV}^2$, the data drops off. This drop can be explained by interference between two indisinguishable possibilities: nucleus 1 emits a photon which interacts with nucleus 2, or vice-versa [10]. In pp or AA collisions, these two possibilities are related by a parity transformation. Since the ρ^0 is negative parity, the interference is destructive. At mid-rapidity,

$$\sigma = \sigma_0[1 - \cos(p_T b)] \tag{5}$$

Of course, b is unknown, and the overall interference depends on the integral over all b. Away from $y = 0$, the interference is reduced because the photon energies, fluxes, amplitudes *etc.* for the two directions are different. The solid curve in Fig. 1 shows a fit to a functional form based on these factors; for this sample, the interference is $101 \pm 8(\mathrm{stat.}) \pm 15(\mathrm{syst.})\%$ of that expected [12]. Because the two sources are spatially separated, the final state $\pi^+\pi^-$ wave function does not factorize into single-particle wave functions, and the system exhibits the Einstein-Podolsky-Rosen paradox [11]. For $\overline{p}p$ collisions, the transformation between the two possibilies is a charge-parity transformation; vector mesons are CP positive, so the interference in Eq. 5 is positive [13]; this may be studied at the Fermilab Tevatron.

STAR has also studied ρ^0 production in dAu collisions. The photon is usually emitted by the gold nucleus, and the deuteron is the target. Both coherent (deuteron stays intact)

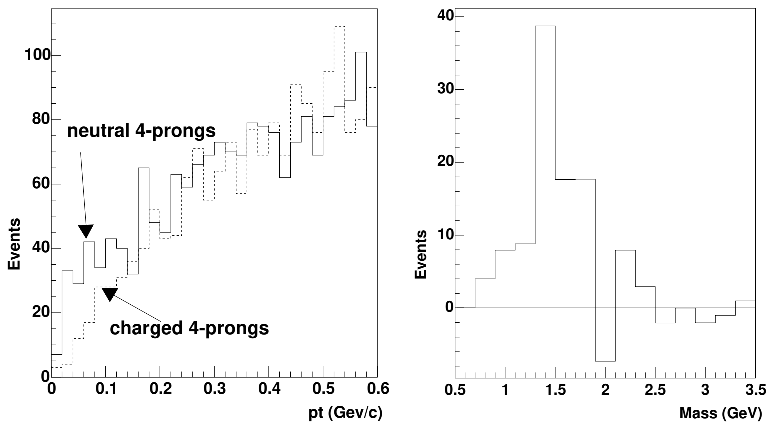

FIGURE 2. (a)p_T spectrum (dN/dp_T) for 4-prong events for neutral and net-charged combinations. (b) The mass spectrum for the neutral excess is peaked around 1.5 GeV.

and incohent (deuteron dissociates) interactions have been observed. The $t_\perp$ spectrum for the incoherent interactions is similar to that observed in eA collisions at HERA [14].

The STAR e^+e^- data is well described by lowest order quantum electrodynamics and factorization [8]. The p_T spectrum of the e^+e^- pairs is not well described by the virtual photon paradigm - the photon virtuality is required to fit the data.

STAR has also studied 4-prong final states, like $\pi^+\pi^-\pi^+\pi^-$. Fig. 2 compares the p_T spectrum of 4-prong events with net charge 0 with those of net charge 2. This data was taken in 2002 with the minimum-bias trigger. A neutral excess is present for $p_T < 150$ MeV/c, with the mass spectrum of the excess centered around 1.5 GeV/c^2.

This work was supported by the U.S. D.O.E. under Contract No. DE-AC-03076SF00098.

REFERENCES

1. C. A. Bertulani, S. R. Klein and J. Nystrand, nucl-ex/0502005.
2. G. Baur *et al.*, Phys. Rept. **364**, 359 (2002).
3. F. Krauss, M. Greiner and G. Soff, Prog. Nucl. Part. Phys. **39**, 503 (1997).
4. J.D. Jackson, *Classical Electrodynamics*, 2nd ed. (Wiley, 1975).
5. G. Baur *et al.*, Nucl. Phys. **A729**, 787 (2003).
6. A.J. Baltz, S. Klein and J. Nystrand, Phys. Rev. Lett. **89**, 012301 (2002).
7. C. Adler *et al.* (STAR Collaboration), Phys. Rev. Lett. **89**, 272302 (2002).
8. J. Adams *et al.* (STAR Collaboration), Phys. Rev. **C70**, 031902 (2004); V. B. Morozov, nucl-ex/0403002.
9. S. Klein and J. Nystrand, Phys. Rev. **C60**, 014903 (1999); L. Frankfurt, M. Strikman and M. Zhalov, Phys. Rev. **C67**, 034901 (2003); V. P. Goncalves and M. V. T. Machado, hep-ph/0501099.
10. S. Klein and J. Nystrand, Phys. Rev. Lett. **84**, 2330 (2000); K. Hencken, G. Baur and D. Trautmann, hep-ph/0506014.
11. S. Klein and J. Nystrand, Phys. Lett. **A308**, 323 (2003).
12. S. Klein, nucl-ex/0310020; S. Klein, nucl-ex/0402007.
13. S. Klein and J. Nystrand, Phys. Rev. Lett. **92**, 142003 (2004).
14. S. Timoshenko, nucl-ex/0501010.