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HOT TOPICS IN ULTRA-PERIPHERAL ION COLLISIONS

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Ultra-peripheral collisions of relativistic heavy ions involve long-ranged electromagnetic interactions at impact parameters too large for hadronic interactions to occur. The nuclear charges are large; with the coherent enhancement, the cross sections are also large. Many types of photonuclear and purely electromagnetic interactions are possible. We present here an introduction to ultra-peripheral collisions, and present four of the most compelling physics topics. This note developed from a discussion at a workshop on "Electromagnetic Probes of Fundamental Physics," in Erice, Italy, Oct. 16-21, 2001.

1   What are Ultra-Peripheral Collisions?

Ultra-peripheral collisions are interactions that occur at impact parameters, b large enough that no hadronic interactions can occur. In simple terms, $b > 2R_A$, where R_A is the nuclear radius. Only electromagnetic interactions are possible; they can be purely electromagnetic ('two-photon') or photonuclear(γA).

Ultra-peripheral collisions of heavy ions are interesting because the large ion charge (Z) gives rise to extremely intense short-duration electromagnetic fields. Following the Weizsäcker-Williams method, these fields are usually described as a spectrum of almost real (quasireal) photons. When the photon wavelength is larger than the nucleus, the emission is coherent and the flux is proportional to Z^2. For relativistic particles with Lorentz boosts γ (to the lab frame), this occurs for lab-frame photon energies $k < \gamma \hbar c/R_A$. In the target nucleus rest frame, photons from the other nucleus have a maximum energy of $(2\gamma^2 - 1)\hbar c/R_A$, about 500 GeV at the Relativistic Heavy Ion Collider (RHIC) at BNL, and 1 PeV at the Large Hadron Collider (LHC) at CERN. RHIC and LHC are high-luminosity γA colliders; LHC has an energy reach far beyond other existing or planned machines. Figure 1 shows the ratio of the γA to AA luminosity for heavy ions at RHIC and the LHC; γp collisions may also be of interest. Also shown, for comparison, is the ratio for the proposed eRHIC electron-ion collider.
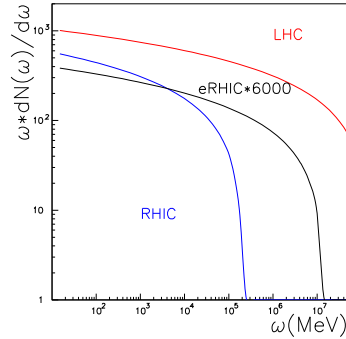
Figure 1: The relative γA:AA luminosity at RHIC and the LHC, compared with that expected at the proposed eRHIC.[2] The eRHIC curve has been multiplied by 6000, the ratio of the planned eRHIC luminosity to the RHIC design luminosity. The photon energy ω is that in the target nucleus rest frame.

The maximum $\gamma\gamma$ collision energy $W_{\gamma\gamma}$ is $2\hbar c\gamma/R_A$, about 6 GeV at RHIC and 200 GeV at the LHC. Figure 2 compares the $\gamma\gamma$ flux at the LHC with the completed LEP II e^+e^- collider at CERN. The LHC will have a significant energy and luminosity reach beyond LEPII, and could be a bridge to $\gamma\gamma$ collisions at a future e^+e^- linear collider.

These cross section enhancements extend the physics reach of heavy ion colliders. For example, the coherent ρ production rate at RHIC is $120 s^{-1}$ with gold, rising to $230,000 s^{-1}$ with calcium at the LHC. The LHC is a vector meson factory. The cross section for e^+e^- production reaches 200 kb for lead at the LHC.[1] Many processes are unique to heavy ion colliders, either because of the high$-Z$ beam particles or because of interference between $\gamma\gamma$ and coherent γA processes.

Ultra-peripheral processes have striking signatures. Two-photon and photon-Pomeron processes lead to final states with a small number of centrally produced particles, with rapidity gaps (regions of phase space containing no particles) separating the central final state from both beams. In addition, neither nucleus should be broken up. For coherent photon emission, the photon perpendicular momentum p_T is less than $\hbar/R_A$. If the coupling to both nuclei is coherent, the transverse momentum p_T of the final state is less than $2\hbar/R_A \approx 100$ MeV/c. Even incoherent interactions (with respect to one of the nuclei) such as photoproduction of heavy quarks will be characterized by a single rapidity gap and intact nucleus.

We present four compelling physics topics for ultra-peripheral collisions: gluon shadowing in nuclei, Pomeron coupling to nuclei, interferometry with short-lived particles and searches for new physics, most notably by studying the γWW vertex. Numerous other interesting subjects, many unique to heavy ion collisions, are not included, either because they require specialized apparatus to study, or because the physics is not yet clearly defined. For example, electromagnetic production of e^+e^- pairs tests QED in the non-perturbative, strong-field regime created by the high-Z sources, but requires a dedicated experiment. Production of lepton or hadron pairs accompanied by capture of the negatively charged particle also fall into this category. Interference between identical final states (like $\pi^+\pi^-$ or e^+e^-) produced via $\gamma\gamma$ and γA channels is sensitive to the relative phases of many processes. This interference is very interesting, but we don't know exactly what to measure yet. Additional details and other peripheral collisions physics are presented in several recent reviews.[1]

2   What is the most interesting physics?

These four topics presented are highlighted for their strong physics interest and their feasibility with existing and planned detectors (possibly with slight modifications).

2.1 Gluon Shadowing in Nuclei

The parton distributions (structure functions) of heavy nuclei is of interest because the low-x gluon density is high, and, in fact, gluon saturation should be present. These strong fields could be a colored glass condensate, with new and unexpected properties.[3] Even in the absence of a condensate, accurate measurements of the parton distributions are important in understanding the initial states of relativistic heavy ion collisions.

To date, most measurements of parton shadowing in nuclei have relied on lepton deep inelastic scattering (DIS). DIS is only sensitive to the quark content of the nuclei; the gluon content is inferred from the Q^2 evolution of the structure functions. Furthermore, the only data on nuclear structure functions is from fixed target experiments, limited to fractional momenta $x > 10^{-3}$ and low momentum transfer.

The gluon distributions can be measured at heavy ion colliders by studying photoproduction of heavy (charm and bottom;[4,5] top is also observable at the LHC[6]) quarks; this reaction occurs primarily by photon-gluon fusion. RHIC will be able to extend the previous measurements to higher Q^2, while the LHC will be able to reach much smaller x and higher Q^2. The LHC measurements will probe regions where many models predict that gluon saturation will be observed. For example, in a colored glass model,[7] photoproduction of charm and bottom at the LHC is much less than is expected in conventional parton distributions.

In photoproduction, the photons are almost real, but the high mass and p_T of the produced heavy quarks introduces a high Q^2 scale. These events can be separated from heavy quark production in grazing hadronic interactions by requiring one rapidity gap in the event, along with one undisturbed nucleus, with a charged particle multiplicity cut to eliminate more central hadronic collisions.

The heavy quark production cross sections are sensitive to the heavy quark mass and to higher-order corrections. Despite this, RHIC and the LHC can offer a 'first look' at as yet unexplored regions of x and Q^2. More importantly, by comparing the heavy quark production in AA (effectively γA) and pA (effectively γp) collisions, the shadowing of nuclear particle distributions can be measured. In the ratio, the QCD uncertainties cancel, and the achievable accuracy should be sufficient for a meaningful measurement of shadowing. It is difficult to obtain these structure functions from other methods. The leading alternative, studies of jets, direct photons and the like in pA collisions at RHIC and the LHC suffers from large systematic uncertainties.

2.2 Pomeron Couplings to Nuclei

Many hadronic interactions do not involve color exchange. Examples include proton-proton elastic scattering, photoproduction of vector mesons, and other diffractive phenomena, including jet and $W^{\pm}$ production. These processes are generally described in terms of Pomeron exchange.

The Pomeron has a long and complex history. It is generally agreed that it involves the strong force, but is colorless, and that it has the quantum numbers of the vacuum ($J^{PC} = 0^{++}$). Beyond that, there is a great diversity of views as to its structure.[8] There are two classes of Pomeron models corresponding to hard and soft interactions. The soft Pomeron represents the absorptive part of the scattering cross section. Often, this is dressed up in Regge theory. It describes much data, including elastic scattering and photoproduction of vector mesons, but lacks internal detail, and a connection to QCD. In photoproduction of vector mesons, a photon fluctuates to a $q\bar{q}$ pair. This pair then scatters elastically (via Pomeron exchange) from the nucleus, emerging as a vector meson.

The hard Pomeron model usually applies for higher momentum transfers, where QCD is expected to be reasonably perturbative. The hard Pomeron is usually modeled as two gluons, with additional structure, such as a gluon ladder.
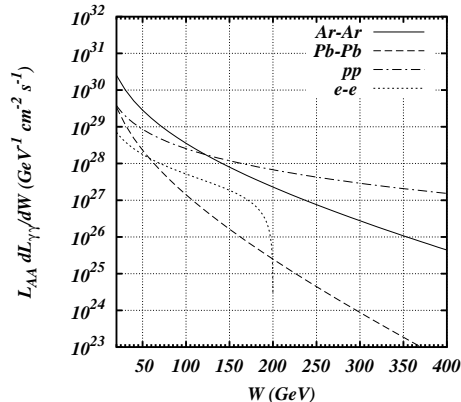
Figure 2: The effective $\gamma\gamma$ luminosity as a function of the $\gamma\gamma$ energy $W_{\gamma\gamma}$ at the LHC, compared with that at LEP II. The AA and e^+e^- luminosities are $ArAr$: $5.2 \times 10^{29}cm^{-2}s^{-1}$, $PbPb$: $4.2 \times 10^{26}cm^{-2}s^{-1}$, pp: $10^{33}cm^{-2}s^{-1}$ (corresponding to about 1 collision/ beam crossing; the LHC pp design luminosity is 10 times higher), and e^+e^-: $5 \times 10^{31}cm^{-2}s^{-1}$ at an e^+e^- center of mass energy of 200 GeV.

One test of these models is their coupling to nuclei. The soft Pomeron couples equally to all nucleons. For heavy states like J/ψ and Υ, the cross section for coherent photonuclear production of vector mesons scales as A^2. For lighter mesons, a single $q\bar{q}$ state can interact with multiple Pomerons; this can be calculated accurately in the Glauber model. In the 'black-disk' limit (very large $q\bar{q}$ states), the cross section scales as $A^{4/3}$.

However, if the Pomeron is made of gluons, the situation changes. The gluon distributions of nucleons change when they are placed in nuclei (the EMC effect/shadowing). If Pomerons are made of gluons, and if the gluon content of nuclei is different from that in independent nucleons, then the Pomeron coupling should change. These couplings can be studied systematically by comparing production rates of different mesons at different p_T from different targets. For $p_T < \hbar/R_A$, the mesons couple coherently to the entire nucleus, while at higher p_T, the coupling is to individual nucleons. The two types of interactions have different properties, and will provide useful cross-checks.

Measurements at LHC will extend the photoproduction cross section measurements to energies significantly above the HERA regime. HERA data for the J/ψ finds $\sigma \approx W^{0.8}$. [9] This rapid increase with γp center-of-mass collision energy W cannot continue indefinitely or the J/ψ cross section will exceed the total photoproduction cross section. A similar rise is seen for the Υ, albeit with lower statistics. [10] The γp cross sections can be measured with pA collisions; LHC can reach an order of magnitude beyond HERA in W.

Heavy meson production in AA (γA) collisions is of interest because of its sensitivity to gluon saturation. [11] The LHC can study nuclear vector meson photoproduction at previously unavailable energies. The cross section is a probe of the gluon density in very low-x, high-A region where many models predict that saturation should be observed. The meson mass and p_T variation will cover the ranges usually described by the hard and soft Pomerons.

2.3 Interferometry with Short-Lived Particles

For coherent γA processes, the two nuclei act as an interferometer, with two nuclei serving as sources. Because the electromagnetic field has a long range, and the hadronic scattering a short range, vector meson production is well localized at the two sources, especially compared with the typical impact parameters of 20-60 fm at RHIC, rising to 20-250 fm at the LHC. The sign of the interference depends on the final state parity.

Because most of the vector mesons have lifetimes far shorter than the time needed to travel
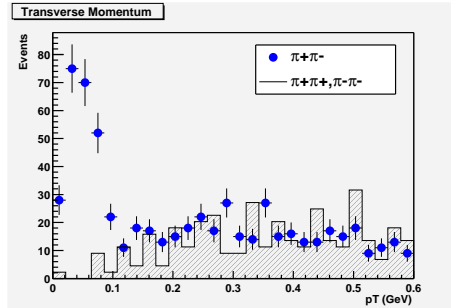
Figure 3: The p_T spectrum of two-track events observed by the STAR detector. The large peak for $p_T < 100$ MeV/c is expected for coherent production of ρ mesons.

between the two nuclei, amplitudes from the two sources must decay independently. This seems to preclude interference; consider, for example, one source decaying $J/\psi \to e^+e^-$ and the other $J/\psi \to \pi^+\pi^-\pi^0$. Yet, quantum mechanics requires that they interfere. The resolution to this paradox is that the post-decay wave functions must contain amplitudes for all possible decay modes: branching ratios, angular distributions, and even decay times. Because this requires a spatially distributed (non-factorizable) wave function, the system is an example of the Einstein-Podolsky-Rosen paradox. It is a test of quantum mechanics for unstable particles. The interference is destructive for $\vec{p}_T \cdot \vec{b} < \hbar$, so the vector meson production is reduced for $p_T < \hbar/\langle b \rangle$. [12] As the data from the STAR detector in Fig. 3 shows, in this region, a clean sample of mesons with $p_T < \hbar/R_A$ can be selected with simple cuts. [13]

Multiple vector meson production is also observable in the strong fields. The probability of ρ production in grazing collisions μ is about 1% with gold at RHIC, rising to 3% with lead at the LHC. [14] If each meson is treated independently, then the probability of producing n ρ at RHIC and LHC are $P(n) = \exp{(-\mu)}\mu^n/n!$, or, for $n = 2$, $(1\%)^2/2$ and $(3\%)^2/2$, for $n = 3$, $(1\%)^3/6$ and $(3\%)^3/6$. The total rates are obtained by integrating $P(b)$ over impact parameter; the doublet rates are large (10^6/year for $\rho^0\rho^0$ at both RHIC and the LHC), while the triplets are still observable.

These samples can be used to study quantum correlations; the final state is considerably richer than for single mesons. The two source ions can each emit single or multiple photons. Production correlations should produce Hanbury-Brown Twiss (HBT)-like enhancements at small relative momentum. However, because the vector mesons can be produced literally on top of each other, many new phenomena may be observable. For example, the vector mesons could interact with each other, leading to new final states such as $\rho^+\rho^-$. Finally, since for relative momenta, $\delta p < \hbar/\tau$, coherence will be maintained until the mesons decay, correlated (stimulated) decays will be possible.

Vector meson lasing occurs for $\mu \geq 1$, depending on the source geometry. Unfortunately, $\mu = 1$ seems unreachable. However, even superradiant behavior should be visible even at the expected $\mu = 0.01 - 0.03$. As the previous paragraph shows, this leads to very interesting phenomenology.

The strong field sources and unique geometry (two identical meson sources) produce a new configuration - an interferometer for short-lived particles. The system is new, and much theoretical and experimental work is required to exploit it. Experimentally, clean samples of coherent vector meson production have been extracted, and initial measurements of interference are not far off.

Two-photon physics at the LHC allows for a wide range of searches for new physics; as Fig. 2 shows, the LHC will have an energy/luminosity reach considerably beyond LEP2. The triple gauge coupling γWW can be studied using the copious two-photon W pair production. This is believed to be the most sensitive process to the new physics of large extra dimensions.[15] Two-photon production of Z pairs or the Higgs boson is less copious, but could complement more conventional studies at the LHC, and test for deviations from the Standard Model predictions. In addition, two photon production rates of the supersymmetric charginos and sleptons are significant.[16]

Because of the high center of mass energies, luminosity and running time, searches for new physics with $\gamma\gamma$ interactions will be most competitive with pp mode at the LHC (see Fig. 2). The hadronic backgrounds can be reduced by requiring that there be rapidity gaps in the event and tagging the forward scattered protons.[17] The LHC magnets will act as magnetic spectrometers for the scattered protons, allowing the reconstruction of the photon momenta. This will give an unbiased estimate of the photon-photon collision energy. It will also allow for significant background rejection.

Tagging will also detect double-Pomeron interactions. Two-photon interactions can be separated from these double-Pomeron interactions because the Pomerons have a larger average transverse momentum than the photons. Depending on the final state under consideration, either single or double tagging may be used. The anticipated luminosity of the tagged two-photon collisions at $W_{\gamma\gamma} > 100$ GeV reaches then almost 1% of the pp luminosity, even for rather conservative assumptions on the tagging efficiency.[16]

Especially at RHIC, tagged double Pomeron interactions are of strong interest to study meson spectroscopy. For reasons that are poorly understood, when the transverse momentum transfer from the protons are in the same direction, conventional $q\bar{q}$ mesons are produced, while when the transverse momentum transfers are in opposite directions, many suspected exotic (non $q\bar{q}$) mesons are preferentially produced.[18]

Single tagging is also possible for pA collisions. The $W_{\gamma\gamma}$ reach is lower, but up $W_{\gamma\gamma} \approx 100$ GeV the pA two-photon luminosity is very competitive with the pp case. This channel can also be used to cross-check two-photon studies using pp and AA.

3   Conclusions

We have presented four compelling examples of the physics accessible in ultra-peripheral collisions. They address a variety of new physics, including relatively straightforward, but important measurements of nuclear shadowing, studies of the nature of the Pomeron, and tests of quantum mechanics and searches for new physics. Many other hadronic measurements are possible with existing detectors.

If experiments requiring new hardware were considered, many other processes would compete for spaces on the list. Many interesting atomic physics experiments are possible. For example, near-threshold single and multiple e^+e^- pair production probes QED in a nonperturbative regime. Pair production with e^- capture is important because it limits the maximum luminosity achievable with heavy ions at the LHC.

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