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SEARCH FOR PHOTINOS AT FUTURE HADRON COLLIDERS

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A B S T R A C T

Neutrino experiments have searched for photinos born in the decays of supersymmetric hadrons produced in a beam dump. Their negative results constrain the domain of possible gluino and squark masses. The luminosity of future pp colliders may be high enough to view their interaction regions as low density "dumps" of one beam into the other. We point out that a search for photinos produced in these machines may very significantly extend the explored domain of supersymmetric parameters.

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Alleged signatures for the production of supersymmetric particles in hadron collisions often involve events with an energy and momentum unbalance. The lightest relevant superparticle - generally assumed to be the photino ($\tilde{\gamma}$) - interacts very weakly, escapes unhindered from conventional detectors and may carry away a "missing momentum". Should the "missing p_T " events recently observed at CERN's $\bar{p}p$ collider¹⁾ find a plausible explanation within a supersymmetric model (still a very open question), photinos may face the fate of neutrinos after their invention by Pauli²⁾ in 1933 and prior to their detection by Reines and collaborators³⁾ in 1959. That is, photinos or other mythological beasts may be implied by momentum conservation, but remain unobserved for quite some time.

Direct searches for weakly interacting particles other than neutrinos have been made in beam dump experiments, most recently at CERN⁴⁾ and Fermilab⁵⁾. We recall that the search is based on the following scenario (a word that has recently gained general acceptance amongst theatrical physicists). Gluinos ($\tilde{g}$) are strongly produced in proton-nucleon collisions, $pN \rightarrow \tilde{g}X$, and they exit dressed up as hadrons ($\tilde{g}g, \tilde{g}q\bar{q}, \dots$). If the gluino lifetime is short enough, these hadrons decay via the elementary process $\tilde{g} \rightarrow qq\tilde{\gamma}$, before they reinteract in the dump. Thus, a "prompt" beam of photinos is generated. Downstream of the dump a shielding absorbs all produced particles but ν 's and $\tilde{\gamma}$'s. Downstream of the shielding, a detector measures charged current ν -induced interactions and neutral current-like events. An excess of neutral current-like events over the value predicted by the standard model would be attributed to $\tilde{\gamma}$ -induced reactions; the "semiweak" process $\tilde{\gamma}q \rightarrow \tilde{g}q$ and the "weak" process $\tilde{\gamma}q \rightarrow \tilde{\gamma}q$. In all the above we have assumed squarks, $\tilde{q}$, to be heavier than gluinos, an attitude that we shall, for the sake of definiteness, maintain. For $m(\tilde{q}) > m(\tilde{g})$ both the gluino decay rate and the photino-nucleon scattering cross-section approximately scale as $[m(\tilde{q})]^{-4}$. The photino mass is expected in most supermodels⁶⁾ to be of the order of $(\alpha/\alpha_s) m(\tilde{g})$ and is effectively neglected in the analysis of beam-dump results. These (negative) results are shown in Fig. 1 as (model-dependent) experimentally excluded regions in the $m(\tilde{q}), m(\tilde{g})$ plane⁷⁾. The lines of constant gluino lifetime labelled $\tau = 10^{-10}, 10^{-11}$ secs. correspond to the cut-off implied by reinteractions of the gluinos in the dump, prior to their decays into photinos. The region above the line labelled 10^{-8} s is presumably excluded by searches for "stable" particles⁷⁾.

The pp hadron colliders presently being discussed - the SSC and the LHC - are planned for such high luminosity ($\mathcal{L} = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$) that their intersection regions may in a sense be viewed as dumps, with one of the proton beams being continuously "dumped" on the other. Most of the particles produced in the

primary interactions (pions and kaons) fly forward and backward and interact with the accelerator components or the tunnel walls before they decay. But shorter-lived particles, such as charmed ones, decay within the vacuum pipes: they constitute a useful "prompt" source of neutrinos and muons, that may be exploited in a completely "parasitic" fashion. A detector along a tangent to a beam at an interaction point, placed after a certain amount of shielding, could do useful physics with the produced neutrinos and muons⁸⁾. [Unlike in a conventional neutrino experiment, the shielding need not be long enough to absorb the muons, since the muon beam is practically a DC one and does not overwhelm the detector. The detector, therefore, can be placed fairly close to the interaction point and cover a significant solid angle.]

In this paper we point out that a direct search for photinos - similar to past beam dump searches - can be performed at future colliders. The photinos originate in the decays of gluinos produced at the collider's primary collisions. The photino detector is the "neutrino" experiment described in the previous paragraph. We shall see that the regions of the $m(\tilde{g})$, $m(\tilde{q})$ plane that can be indirectly explored in a photino search at future colliders extend considerably beyond the present beam dump limits.

In its present form, QCD is of no help to us in the computation of the "diffractive" or the total gluino-production cross-section in proton-proton collisions. Yet, the production of pions, strange particles, antiprotons and charmed particles can be parametrized by a universal function^{8),9)}:

$$\begin{aligned} n(s, M) &\equiv \sigma(pp \rightarrow M + \dots) / \sigma_{\text{tot}}(pp) = f(\omega) / M^2 \\ \omega &= (s - s_{\text{TH}}) / M^2 \\ f(\omega) &\simeq (0.4 \text{ GeV}^2) (0.15 \ln \omega + 3.3 \omega^{-1/2} - 1) \end{aligned} \tag{1}$$

where M is the mass of the produced particle, and s_{TH} is the square of the threshold invariant energy for its production. Equation (1) reproduces the observed particle production rates to within a factor 2 or 3. We shall assume that the production of gluino-containing hadrons follows the universal law of Eq. 1. Let x be the fraction of the original proton's energy carried by the gluino-containing hadron, and let p_T be its transverse momentum. For the differential production cross-section, we assume the shape

$$\frac{d\sigma(pp \rightarrow \tilde{g} + \dots)}{dx dp_T^2} \sim D(x) \exp \left\{ -b (m^2(\tilde{g}) + p_T^2)^{1/2} \right\} \quad (2)$$

where $b \approx 3.45 \text{ GeV}^{-1}$ is a fit to the data for the production of pions and kaons, compatible with the data on charmed particles. $D(x)$ is the assumed longitudinal distribution of gluino-containing hadrons, with x their fraction of the proton's longitudinal momentum. We shall assume $D(x) = (n+1)(1-x)^n$, and give explicit results for $n = 5$, a fairly pessimistic choice. [A smaller value of n would imply harder gluinos and photinos and consequently, a bigger photino cross-section]. Let $z = E(\tilde{\gamma})/E(\tilde{g})$ in the elementary decay $\tilde{g} \rightarrow \tilde{\gamma} q \bar{q}$ and let θ be the angle between the photino and gluino momenta. In the approximation that $E^2(\tilde{g}) \gg m^2(\tilde{g})$, and for $m^2(\tilde{q})$ not very close to $m^2(\tilde{g})$, the differential $\tilde{g} \rightarrow \tilde{\gamma}$ decay rate can explicitly be computed to be

$$\frac{1}{\Gamma} \frac{d\Gamma(\tilde{g} \rightarrow \tilde{\gamma})}{dz d\theta^2} = G(z) E^2(\tilde{g}) [m^2(\tilde{g}) + \theta^2 E^2(\tilde{g})]^{-2}$$

$$G(z) = (5 - 4z^2 + 9z^3) / 3 \quad (3)$$

In practice we shall assume $E_p \approx 8$ and 20 TeV . In this case, and for $m(\tilde{g}) \gtrsim 3 \text{ GeV}$, the angular spread of the photino beam, relative to the incident protons, is dominated by the $\tilde{g} \rightarrow \tilde{\gamma}$ decay angular spread of Eq. (3), the detailed shape of the p_T distribution assumed in Eq. (2) is irrelevant.

The $\tilde{\gamma} \mathcal{N} \rightarrow \tilde{g} X$ cross-section on an isoscalar target is⁹⁾

$$\sigma(\tilde{\gamma} \mathcal{N}) = H E(\tilde{\gamma}) \int_0^1 y dy F(y) \left[1 - \frac{m^2(\tilde{g})}{2m_p y E(\tilde{\gamma})} \right] \theta [2m_p y E(\tilde{\gamma}) - m^2(\tilde{g})]$$

$$H \equiv \frac{320\pi}{81} \frac{\alpha \alpha_s}{m^4[\tilde{q}]} m_p^2 \sim 4 \cdot 10^{-36} \text{ cm}^2 \left(\frac{40 \text{ GeV}}{m[\tilde{q}]} \right)^4 \left(\frac{\alpha_s}{0.3} \right) \quad (4)$$

Here, $F(y) \sim 4(1-y)^3$ is the assumed normalized quark structure function, in an average nucleon $[\mathcal{N} = (p+n)/2]$. The quarks have been taken to carry on the average 50% of the proton momentum. The gluino mass-dependent factors in Eq. (4) reflect the gluino production threshold. [At large gluino masses the weak channel $\tilde{\gamma} \mathcal{N} \rightarrow \tilde{\gamma} X$ may compete with the semiweak threshold-suppressed $\tilde{\gamma} \mathcal{N} \rightarrow \tilde{g} X$ channel. We have taken this small effect into account in our final results.]

With the information in the above paragraphs, we can proceed to compute the interaction rate R in a detector of length L and average density ρ . Let θ be the angle of the photino with the original proton beam direction. The number of photino interactions per second in a bin $d\theta^2$ is

$$\frac{dR}{d\theta^2} = B \int_b^1 x^3 D(x) \left[1 + \left(\frac{E_p x \theta}{m(\tilde{g})} \right)^2 \right]^{-2} \int_{b/x}^1 z G(z) dz \int_{b/xz}^1 y F(y) [1 - b/xyz] dy$$

$$b = m^2(\tilde{q}) / (2m_p E_p)$$

$$B = \frac{1}{2} E_p^3 m^{-4}(\tilde{g}) f(\omega) \sigma_{TOT}(pp) \mathcal{L} \rho N_A L H \quad (5)$$

where N_A is the Avogadro di Quaregna number (nucleons/gram) and all other factors should be clear from the above discussion, except for the factor $\frac{1}{2}$ in the definition of B . This factor originates from the fact that our scaling law for particle multiplicities, Eq. (1), counts all particles in the final state, while in our colliding beam situation only half of the produced particles, on average, fly to one side or the other.

The background to a photino search are neutrino neutral current interactions. They are induced by the $\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$ beam that originates in the semi-leptonic decays of charmed and beautiful particles produced at the collider's intersections⁸⁾. [Longer-lived particles have no time to decay in significant proportions, particles heavier than charmed or beautiful ones are less abundantly produced.] In Figs. 2a and 2b, we have drawn these backgrounds (for $E_p = 8$ and 20 TeV, respectively) as $dN/d\cos\theta$ as a function of θ (the angle relative to beam center). The number of events is computed for a machine "year" of operation (10^7 seconds) with a luminosity $\mathcal{L} = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, and for a "standard" detector with an average density $\rho = 5 \text{ g/cm}^3$, and a length $L = 25$ metres. Charmed and beautiful backgrounds are estimated as in Ref. 8), with an assumed x -distribution $\sim(1-x)^3$ for both kinds of heavy particles. In a detector unable to distinguish $\nu_e \rightarrow e$ events from neutral current events, the background is roughly twice the one shown in Fig. 2. Also in Fig. 2, and with the same machine and detector parameters, we have drawn the photino-induced signal as given by Eq. (5) for several choices of $m(\tilde{g})$, with a fixed $m(\tilde{q}) = 80 \text{ GeV}$. Clearly, these examples correspond to supersymmetric parameters that could easily be explored in a "year" of operation. The photino signal favourably competes with the background because the branching ratio $\tilde{g} \rightarrow \tilde{\gamma}$ is assumed to be unity and because the $\tilde{\gamma}N$ cross-section is "semiweak".

In order to make a rough estimate of the highest values of $m(\tilde{q})$ and $m(\tilde{g})$ that could be explored with our imagined detector, we pause to comment on the

comparison between signal and background. First of all, the background neutrino neutral currents can be estimated with fair precision from the observed charged current events, with use of the standard model. In particular, the angular spread and the energy distribution of the neutrino flux can be measured with high statistics. For $m(\tilde{g}) > 5$ to 10 GeV, we expect the photino beam to be much broader than the background ν - beam, see Fig. 2. The signal/noise ratio can be simply improved by moving the detector off-axis. For $m(\tilde{g}) < 5$ GeV, we expect the missing p_T distribution of the background events to be much harder than that of the signal events. The outgoing neutrino in a neutral current process typically carries away a transverse momentum which is a fair fraction of its energy. Likewise, light gluinos are produced with large transverse momentum, but they lose much of their energy in the form of "QCD fragmentation" before they decay and share their remaining momentum between a quark pair and a photino¹¹⁾. The photino leaves with a typical missing p_T much smaller than that of the background neutral current neutrinos. The signal events tend to have a "two-jet" structure: one jet from the fragmentation and decay products of the gluino, another from the final quark in the underlying $\tilde{\gamma}q \rightarrow \tilde{g}q$ reaction. It would be premature to run all of these considerations through the event generator of a hypothetical future detector. We content ourselves with the estimate that 100 signal events per "year", in a detector that subtends 5 mrad of the beam (on or off-axis), can presumably be disentangled from the background. In this case, and upon use of Eq. (5) with the parameters of our hypothetical machine and "standard" detector, we conclude that one can explore the region of $m(\tilde{g})$, $m(\tilde{q})$ masses labelled LHC ($E_p = 8$ TeV) or SSC ($E_p = 10$ TeV) in Fig. 1. To extract a maximum explorable value of $m(\tilde{q})$ at fixed $m(\tilde{g})$ one must take a fourth root of the number of events $[\sigma(\tilde{\gamma}q) \sim m[\tilde{q}]^{-4}]$. Thus our final results are not very dependent on the details of our assumptions.

To conclude, a "neutrino and muon" experiment, working entirely parasitically along a tangent to an interaction point of an intense and energetic pp collider⁸⁾, can explore a large domain of masses of the hypothetical superparticles. It may even be able to discover photinos, in which case a measurement of their mass can be attempted via time of flight techniques. As for neutrinos, this is a much harder enterprise than a run-of-the-mill discovery.

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FIGURE CAPTIONS

Figure 1 Regions of the $m(\tilde{q}), m(\tilde{g})$ plane excludable by past experiments and explorable by future ones.

Figure 2 Neutrino neutral current background and photino signal for $m(\tilde{q}) = 80$ GeV and a variety of gluino masses. The number of events corresponds to a pp luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$, in 10^7 seconds of operation of a "standard" detector defined in the text. a) and b) are for $E_p = 8$ and 20 TeV, respectively.

- Figure 1 -

- Figure 2a -

- Figure 2b -