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Search for events with leptonic jets and missing transverse energy in pp collisions at \( \sqrt{s} = 1.96 \text{ TeV} \)

Hidden-valley models [1] contain a hidden sector that is very weakly coupled to standard-model (SM) particles. By introducing new low-mass particles in the hidden sector, these models have been shown to provide a coherent interpretation [2, 3] of possible astrophysical anomalies [4, 5, 6], and accommodate discrepancies in direct searches for dark matter [7, 8]. The impact of the hidden valley particles should be observable in high-energy collisions [9, 10, 11, 12]. Although details of the hidden sector can affect the phenomenology, the force carrier in the hidden sector, the dark-photon ($\gamma_D$), must have a mass $\lesssim 2 \text{ GeV}$, and generally decays into SM charged-fermion (or pion) pairs. In many models, $\gamma_D$ has a short lifetime, and does not travel an observable distance ($\lesssim 1 \mu\text{m}$) before decaying. If supersymmetry (SUSY) is realized in Nature, there will be partners for both the SM and the hidden sector particles. If the lightest SUSY particle (LSP) of the hidden sector ($\tilde{X}$) is lighter than the lightest SM SUSY partner (SM-LSP), the SM-LSP can decay...
jets will consist only of charged leptons. Even for larger less tightly collimated, and less isolated. producing final-state particles in $\gamma$-jets that are softer, the hidden sector \cite{9} can dilute the $\gamma$-jet signatures, by escaping dark particles. Radiation of additional least two $\gamma$-jets and a large imbalance in transverse energy we therefore refer to them as leptonic jets ($\gamma$-jets). For effective in observing such events \cite{15, 16}.

In this Letter, we present a search for events with two $\gamma$-jets and large transverse momentum ($p_T$) in the central tracker. $\gamma$-jets are analyzed separately, and contain 7344, 19014, and 30642 candidate events, respectively. Each event is assigned to just one class, with preference of $ee$, since muon $\gamma$-jets are studied using MC simulation and are discussed below. The analysis requires two $\gamma$-jet candidates (either muon or electron) in each event. The three classes of $\mu\mu$, $e\mu$, and $ee$ $\gamma$-jets are analyzed separately, and contain 7344, 19014, and 30642 candidate events, respectively. Each event is assigned to just one class, with preference of choice given to $\mu\mu$, then $e\mu$, and then $ee$, since muon $\gamma$-jets have less background. All collected events are used in the analysis, but most pass single or di-lepton triggers \cite{17}. Following offline selections, the trigger efficiency for signal is $>90\%$.

The main background to $\gamma$-jets is from multijet production, but electron $\gamma$-jets also have a contribution

**FIG. 1: A diagram for associated production of SUSY charginos and neutralinos that decay into SM vector bosons and SM-LSPs ($\tilde{X}^0$), each decaying into the LSP of the hidden-sector ($\tilde{X}$) and a dark-photon ($\gamma_D$).**
from photon production with subsequent conversion to $e^+e^-$. Such backgrounds cannot be calculated reliably using simulation, and are therefore determined from data. We exploit the tight collimation of $l$-jets to distinguish them from multijet background, through track and calorimeter-isolation criteria. The “track isolation” is defined by a scalar sum over $p_T$ of tracks with $p_T > 0.5$ GeV, $z < 1$ cm from the seed track at its distance of closest approach to the beamline, and within an annulus $0.2 < R < 0.4$ relative to the seed track. Muon $l$-jet calorimeter isolation ($I_\mu$), defined in Ref. [23], relies on the transverse energies of all calorimeter cells within $R < 0.4$, excluding cells within $R < 0.1$ of either the seed muon or its companion track. For electron $l$-jet isolation, we employ the EM cluster-isolation $I_e$ defined above. A reliable estimate of background requires that the $l$-jet isolation requirements not bias the kinematics, such as distributions in $E_T$ or $p_T$ of $l$-jets. Both types of $l$-jets require the track isolation to be $I_t < 2$ GeV, which does not significantly bias the background. Calorimeter-isolation criteria are chosen as linear functions of $p_T$ values of the $l$-jet, such that the fraction of rejected background is large, but weakly dependent on $E_T$, as discussed below. For EM clusters, we choose $I_e < 0.085 \times p_T - 0.53$ (in GeV units), which rejects 90% of the background. For muon $l$-jets we use the scalar sum of $p_T$ values of the muon and companion tracks as a measure of $l$-jet $p_T$, and require $I_\mu < 0.066 \times p_T + 2.35$ (in GeV units), which rejects 94% of the background. We compare the $E_T$ distribution in data with just one isolated $l$-jet to those containing two (not necessarily isolated) $l$-jets. The two distributions are observed to be very similar, which indicates that the kinematic bias on $E_T$ from $I_e$ and $I_\mu$ requirements is indeed small. We therefore use the $E_T$ distribution in data without isolation requirements as background for the data with two isolated $l$-jets, since both samples are dominated by similar multijet processes.

Finally, we require $E_T > 30$ GeV for the search sample, where $E_T$ is calculated using only calorimetric information, and not corrected for any detected muons, as muon reconstruction is unreliable in $l$-jets because of the presence of nearby tracks. We scale the $E_T$ distribution in the data sample without isolation criteria so that the total number of events with $E_T < 15$ GeV matches that in the isolated data sample, see Fig. 2. The ratio $R_f$ defined as the number of events in each search channel with $E_T > 30$ GeV divided by the scaled number of events with $E_T < 15$ GeV in each respective background is given in Table I. The value of $R_f$ is important since if a signal

![FIG. 2: (color online) The $E_T$ distribution for events with (a) two isolated muon $l$-jets, (b) one muon and one electron $l$-jet, and (c) two electron $l$-jets. The data are presented by the black points, and the shaded bands represent the expected background, with red showing the correlated part of the systematic uncertainty from normalization and blue the full uncertainty. The SPSS MC contribution for signal (see text) is scaled to an integrated content of 10 events. The highest bin contains all events with $E_T > 90$ GeV.](image-url)
TABLE II: Branching ratio ($\mathcal{B}$) into electrons and muons of $\gamma_D$ as a function of its mass. Mass windows for a search for $\gamma_D$, and the efficiency for a reconstructed, isolated $l$-jet to be found in each mass window, for electron and muon $l$-jets.

| $M(\gamma_D)$ (GeV) $\Delta \mathcal{B}/\mathcal{B}_\mu$ $\Delta M(l$-jet)(GeV) $\text{Eff. ee/} \mu\mu$ (GeV) |
|-----------------|-----------------|-----------------|-----------------|
| 0.15            | 1.00/0.00       | 0.0–0.3         | 81/–            |
| 0.3             | 0.53/0.47       | 0.1–0.4         | 82/88           |
| 0.5             | 0.40/0.40       | 0.3–0.6         | 81/89           |
| 0.7             | 0.15/0.15       | 0.4–0.8         | 85/89           |
| 0.9             | 0.27/0.27       | 0.6–1.1         | 82/91           |
| 1.3             | 0.31/0.31       | 0.9–1.4         | 72/79           |
| 1.7             | 0.22/0.22       | 1.0–1.8         | 73/76           |
| 2.0             | 0.24/0.24       | 1.3–2.2         | 73/83           |

has a $E_T$ spectrum similar to that of the background, this analysis would be largely insensitive, regardless of the size of the signal. The total background for a signal having $f_1$ events with $E_T$ < 15 GeV and $f_2$ events with $E_T$ > 30 GeV is a factor of $(f_1/f_2) \times R_f$ larger than for the case of no signal. For the benchmark signals considered, $(f_1/f_2) \times R_f \ll 1$, and the correction is therefore ignored.

We separate the detection efficiency into three components (Table I): (i) the branching ratio ($\mathcal{B}$) for an event to have at least two $l$-jets in the $\mu\mu$, $e\mu$, or $ee$ channel, obtained from the expected $\gamma_D$ branching fractions [13], (ii) the acceptance ($\mathcal{A}$) for both $l$-jets to have the seed and companion tracks within $|\eta| < 1.1$ for electrons and $< 1.6$ for muons, with $p_T > 10$ and 4 GeV, respectively, and $E_T$ (calculated in MC as the vector sum of transverse momenta of all stable particles in the hidden sector, neutrinos, and muons) > 30 GeV, and (iii) the efficiency ($\epsilon$) to reconstruct both $l$-jets in the acceptence, to pass the isolation criteria for both $l$-jets, and to have reconstructed $E_T$ in excess of 30 GeV. The acceptance and reconstruction efficiency do not vary significantly with $M(\gamma_D)$.

With no excess observed above the expected background at large $E_T$ (see Fig. 2), we set limits on $l$-jet production cross sections, using a likelihood fitter [24] that incorporates a log-likelihood ratio statistic [25]. Limits at the 95% CL on cross section times $\mathcal{B}$, calculated separately for the $\mu\mu$, $e\mu$, and $ee$ channels, using the observed numbers of events, predicted backgrounds, and detection efficiencies and acceptances, are given in Table I. Systematic uncertainties are included for signal efficiency (20%), background normalization (20–50%), and luminosity (6.1%). The uncertainty on the signal efficiency is dominated by the uncertainty in the tracking efficiency for neighboring tracks in data. The background uncertainty is dominated by the small remaining kinematic bias on the $E_T$ arising from the isolation criteria.

When the track multiplicity in any $l$-jet is small, the leading track and its companion track are likely to originate from the decay of the same dark photon, so we also examine the invariant mass of the seed and its companion track ($M(\gamma_D)$) in events with two isolated $l$-jets and $E_T > 30$ GeV (Fig. 3). The backgrounds are normalized by scaling the events passing all selections but with $E_T < 20$ GeV to data with $E_T > 30$ GeV outside of the mass windows defined in Tab. II, thus $R_f$ is irrelevant for this second analysis. The selection of background events is loosened to $E_T < 20$ GeV for this resonance search to increase the statistics of the sample. Limits on cross sections are calculated in various ranges of $l$-jet mass, $\Delta M(l$-jet), as shown in Table II and Fig. 4.

The dependence of the efficiency for reconstructing and identifying $l$-jets on parameters of the hidden sector is studied using MC simulation. Additional MC samples are used for examining the neutralino decay into a dark Higgs boson that decays into two dark photons, leading to more, but softer, leptons in $l$-jets. Efficiency for these states decreases by $\approx \frac{1}{2}$ at large $M(\gamma_D)$, for both elec-
Dark photon mass (GeV)

FIG. 4: (color online) Limit on the observed cross section (blue, solid curve) for the three channels combined, corrected for SPS8 acceptance, as a function of $M(\gamma_D)$. Also shown are the observed (blue, circles) and expected (red, squares) combined limit determined using the measured masses of the seed and companion tracks in both $l$-jets, for each mass window studied (from Table II). Limits are weaker when the dark photon branching ratio to hadrons is larger, particularly near the $\rho$ and $\phi$ resonances.

tron and muon $l$-jets. The point $M(\gamma_D) = 0.7$ GeV also has a $\approx 50\%$ lower efficiency, due to the large branching fraction of $\gamma_D$ to hadrons. MC events are also generated with additional radiation in the hidden sector. Raising the dark coupling ($\alpha_D$) from 0 to 0.3 reduces the efficiency by up to 20%, independent of $M(\gamma_D)$. According to MC simulation, the $l$-jet identification criteria maintain good efficiency even for more complicated behavior in the hidden sector.

In summary, we have performed a search for events with two tightly collimated jets consisting mainly of charged leptons and large $E_T$ in 5.8 fb$^{-1}$ of integrated luminosity. The invariant mass of the $l$-jets, formed by a seed track and a companion track was also examined for a resonant signal. No evidence was observed for such signals, and upper limits were set, as a function of $M(\gamma_D)$, on the production cross section for SUSY particles decaying to two $l$-jets and large $E_T$.

We thank A. Falkowski, J. Ruderman, M. Strassler, S. Thomas, I. Yavin, and J. Wacker for many useful discussions and guidance. We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); CRC Program and NSERC (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).

[18] D0 uses a right-handed coordinate system, with the $x$-axis pointing in the direction of the proton beam and the $y$-axis pointing upwards. The azimuthal angle $\phi$ is defined in the $xy$ plane, and is measured from the $x$-axis. The pseudorapidity is defined as $n = -\ln[tan(\theta/2)]$, where $\theta$ is the polar angle.
[22] The lightest neutralino mass for this SUSY point is $\approx 140$ GeV and the second neutralino and the chargino masses are both $\approx 265$ GeV; B.C. Allanach et al., Eur. Phys. J. C 25, 113 (2002).