LLNL-TR-426986

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Trigger Algorithm Design for a SUSY Lepton Trigger based on Forward Proton Tagging

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April 1, 2010

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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Abstract

At the Large Hadron Collider (LHC) pair production of SUSY leptons in gamma-gamma interactions will often include intact off-energy protons. Including detectors in the beampipe to measure these protons can give additional information to separate these events from background. We report on expected event rates and background rejection for a slepton trigger design in the Compact Muon Solenoid (CMS) experiment incorporating forward proton information. We conclude that a trigger that can observe an interesting number of events is feasible with the appropriate detector hardware.

1 Introduction

SUSY leptons pairs are directly produced through virtual photon-photon interactions and quark anti-quark annihilations. Indirectly they are produced in the cascade decays of other higher mass SUSY particles. The SUSY leptons are expected to decay to lepton plus neutralino or neutrino plus chargino. For SUSY lepton pairs produced in exclusive photon-photon interactions, see Figure 1, this leads to a signature of two opposite sign leptons with missing energy and no other activity in the event as the intact protons travel down the beam pipe. For low luminosity this creates a distinct event topology. At the design luminosity of the LHC there are several interactions per bunch crossing and the topology is obscured by extraneous events. Installing detectors at 240 and 420 meters downstream of the CMS detector would allow the intact protons to be observed. Measuring their momentum and arrival time would strongly reject background and allow increased separation of signal from background.

2 Exclusive production of slepton pairs in $\gamma\gamma \rightarrow \tilde{l}^{+}\tilde{l}^{-}$

The two-photon production of right-handed sleptons or other heavy non-Standard Model leptons at hadron colliders has been investigated [1] and is shown in Figure 2. The total cross section at the LHC for the process $\gamma\gamma \rightarrow \tilde{l}^{+}\tilde{l}^{-}$ can be as large as ~ 20 fb, while still being consistent with the best direct search limits from LEP [2] as shown in Figure 3.

The two-photon production process consists of both an inelastic component, in which the photon couples to a quark in the proton and the proton fragments and an elastic component in which the photon is radiated from the proton which remains intact. The cleanest elastic-elastic events in which both protons remain intact is shown in Figure 1, the cross-section for these $pp \rightarrow p\tilde{l}^{+}\tilde{l}^{-}p$ events can be up to ≈ 1 fb without violating the direct search limits.

As shown in Figure 2 the production rate falls off quickly for higher mass sleptons; we therefore restrict this study to low-mass SUSY points where the slepton mass in < 200 GeV and the cross-section is > 0.1 fb. In mSUGRA/CMSSM-like models the slepton branching fraction is typically 100 percent to a lepton and the lightest neutralino ($\tilde{l}^{\pm} \rightarrow \chi_1^0 l^{\pm}$). The final state signature is then two same-flavor opposite-sign leptons and missing energy, plus two off-energy forward protons. In general the signal rate and efficiency for finding these events will depend on two parameters.

1. The slepton mass. As the slepton mass decreases the cross-section becomes larger, but the production becomes less central, resulting in a lower acceptance for the final state leptons. The slepton mass also determines the relative importance of different forward detector positions for identifying the protons (e.g. 220 vs 420 meters).

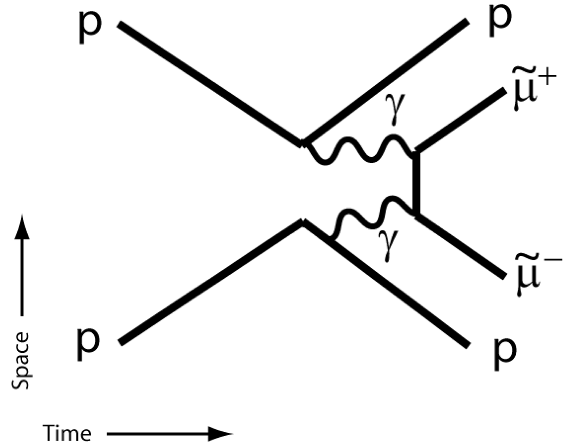

Figure 1: Feynmann diagram of SUSY lepton pair production in the exclusive gamma-gamma channel.

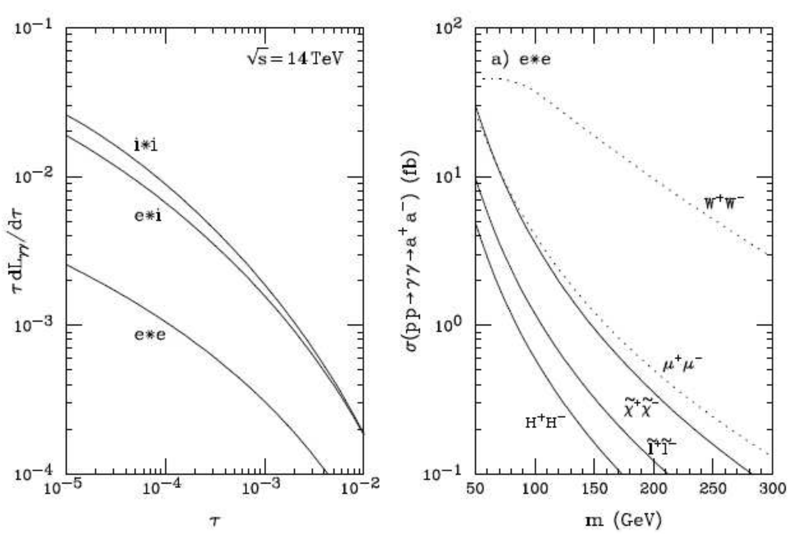

Figure 2: Luminosity for exclusive and inclusive gamma-gamma processes on the left and the cross-sections for exclusive gamma-gamma processes on the right.

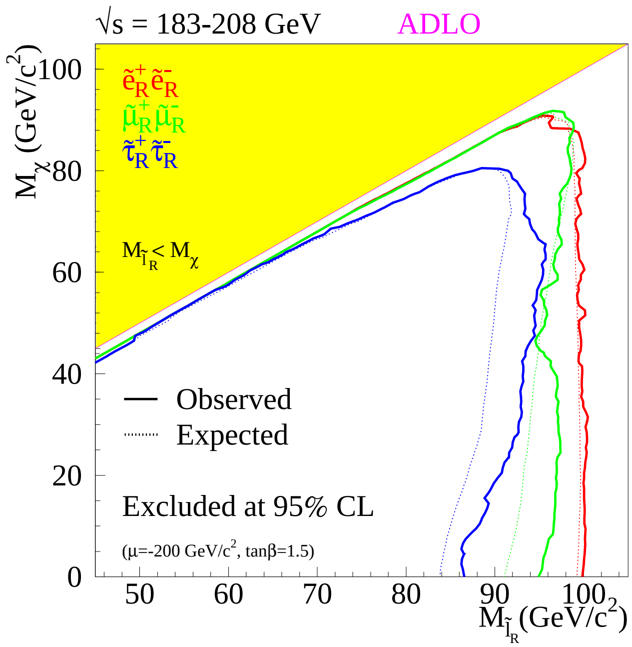

Figure 3: Combined slepton exclusion plot from the Aleph/Delphi/L3/Opal evaluation group. Excluded 95% C.L. in slepton mass versus neutralino mass.

2. The slepton-neutralino mass difference. If the mass difference ΔM is small the lepton p_T will peak at lower values, resulting in a lower trigger/reconstruction efficiency. However, when the difference becomes very small the usual direct LEP limits no longer apply, and the production cross-section could be much larger than normally considered.

The existing direct limits from the combined LEP experiments, see Figure 3, allow for sleptons above $\sim 90 - 100$ GeV, or lower if the mass difference $\Delta m(\tilde{l}^{\pm} - \chi_1^0)$ is small. In this note, three scenarios are studied:

1. The LM1 mSUGRA benchmark point, with $m(\tilde{l}^{\pm}) = 118$ GeV and $m(\chi_1^0) = 98$ GeV.
2. A scenario with $m(\tilde{l}^{\pm}) = 118$ GeV and $m(\chi_1^0) = 112$ GeV.
3. A scenario in which the slepton escapes the LEP searches by being nearly nearly degenerate with the neutralino in mass, with $m(\tilde{l}^{\pm}) = 82.5$ GeV and $m(\chi_1^0) = 77.7$ GeV.

3 Forward Proton Tagging

At low luminosity, when the average number of events per bunch crossing is 1 or less, sleptons can be searched for by looking for their topology of two leptons with missing energy and no other activity in the detector. The primary background is from Standard Model lepton pairs which can be excluded by a acoplanarity cut as shown in Figure 4. An irreducible background comes from the process $\gamma\gamma \to W^+W^- \to l^+l^-\nu\tilde{\nu}$. Using only the information on the muons measured in the central detector only the missing energy of the dimuon system is reconstructable, as shown in Figure 4. This does not provide strong separation between the slepton and W signals.

Rather than identifying exclusive events by looking for an abscence of additional particles in the detectors one could look for the intact protons. Since the protons in these interaction are off-energy they will slowly

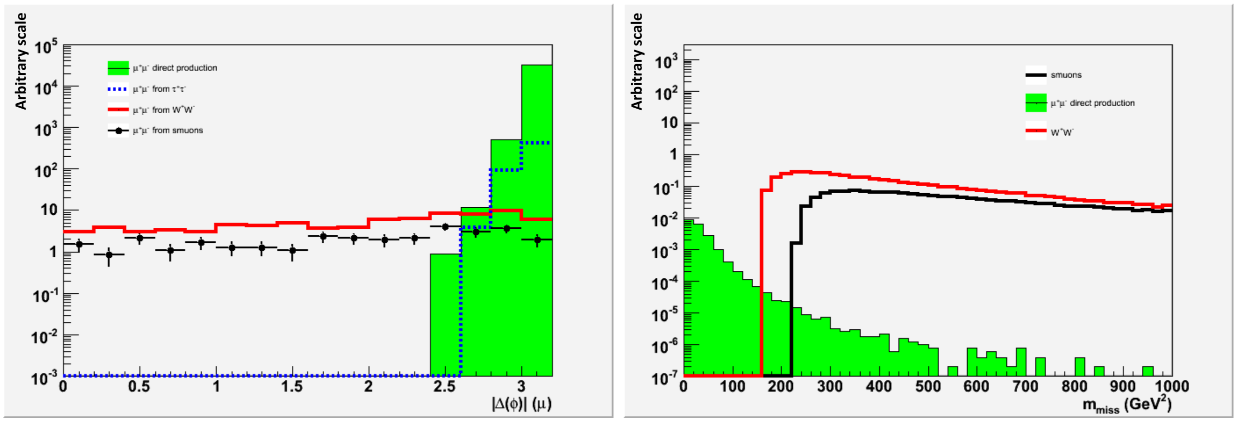

Figure 4: SUSY lepton signal and background distributions for acoplanarity (left) and missing energy (right).

peel away from the beam as it travels through the LHC bending magnets. Detectors placed just inside the beampipe could observe these particles [3]. In the current LHC beamline layout there are areas that could be modified to house detectors at 220 and 420 meters, as shown in Figure 5. Figure 5 shows the layout of the LHC magnets with the trajectories of some representative off-energy protons as calculated by the HECTOR [4] program. Using this program and proposed locations for detectors in the beampipe we can determine the acceptance for the intact protons in slepton pair production events. We used the MadGraph implementation [5], of the Weizsaecker-Williams approximation for the photon flux to generate samples of $\gamma\gamma \to \tilde{\mu}^+\tilde{\mu}^-$ at various masses. Figure 7 shows the acceptance of the forward proton detectors as a function of slepton mass. While the detectors at 220 meters have good acceptance at high slepton mass the addition of the 420 meter detectors is necessary to get good acceptance at all the relevant slepton masses. On the left of the same figure is the expected number of events as a function of slepton mass for the acceptance times the cross-section at 100 fb^{-1}.

The combination of tracking detectors in the beampipe with the bending magnets of the LHC form a high precision spectrometer which can measure the momentum of the protons [3]. Once the momentum of both protons is known the center of mass energy of the interaction can be determined as well as the boost of the system along the beam axis. The two muons measured in the central detector can then be boosted to the center of mass frame. As shown in the right plot of Figure 8 the center of mass distribution shows a sharp cutoff at twice the slepton mass. At that point in phase space the sleptons are produced at rest in the center of mass. As the center of mass increases the sleptons receive an equal and opposite boost in the center of mass frame. In the center of mass frame the muon momentum becomes a function of the slepton - neutralino mass difference and the cosine of the angle between the muon and the slepton direction. At the center of mass edge only one muon momentum is possible. There are now three variables with useful information; center of mass energy and the two muon momenta. This additional information provides a way of determining the slepton and neutralino masses and provides good separation between the sleptons and the irreducible WW background, as shown in Figure 9.

4 Offline reconstruction and signal samples

We use samples of $\gamma\gamma \to \tilde{\mu}^+\tilde{\mu}^-$ generated with the MadGraph implementation [5], of the Weizsaecker-Williams approximation for the photon flux, in which $\mathcal{B}(\tilde{\mu} \to \chi_1^0\mu^\pm) = 100\%$. The full simulation and reconstruction is performed for the central detector, and the Hector [4] proton transport code is used to estimate the acceptance for generator-level protons in the detectors at 220 and 420m. The expected numbers of events per 100 fb^{-1} at $\sqrt{s} = 14$ TeV after accounting for the offline muon reconstruction and proton tag

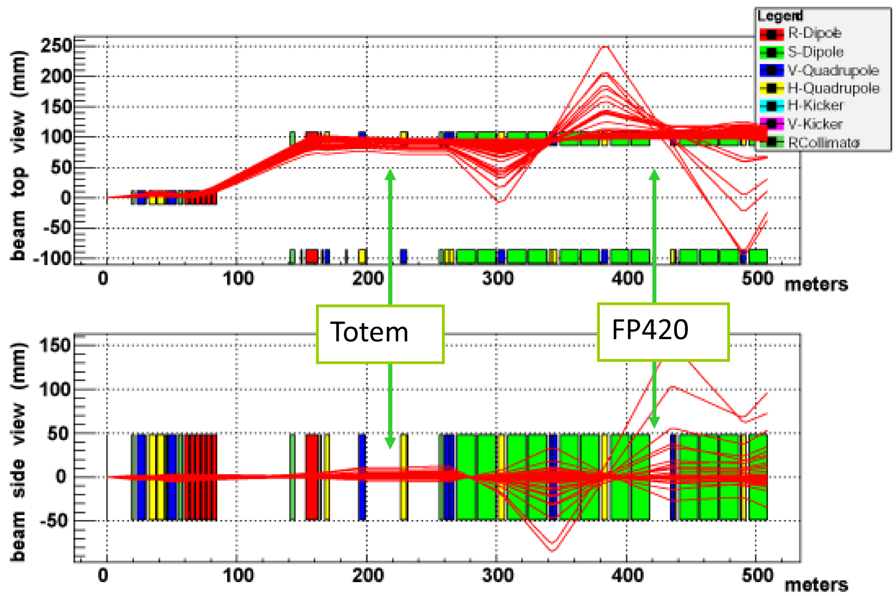

Figure 5: Layout of the LHC beamline showing the magnetic components. Top view and side view. Representative trajectories of off-energy particles are shown.

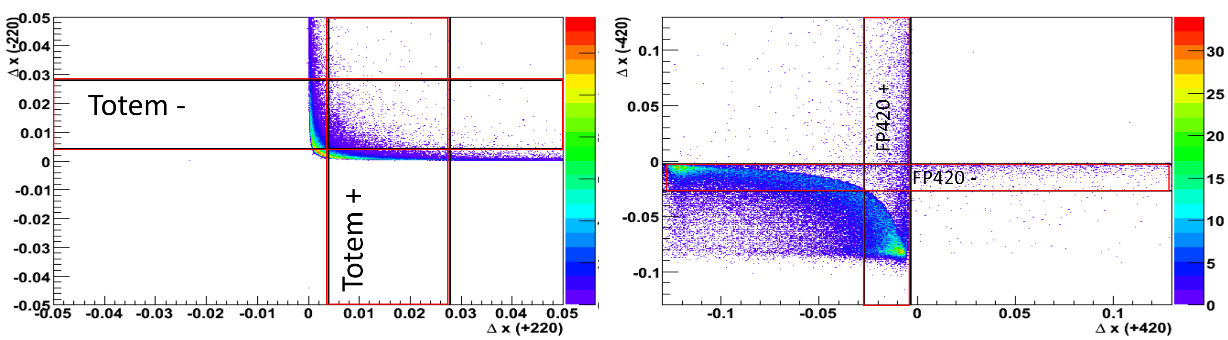

Figure 6: Displacement of the beam in the plane transverse to the beam at both the positive and negative stations for 220 and 420 meter detectors. The bands show the assumed acceptance of the detectors.

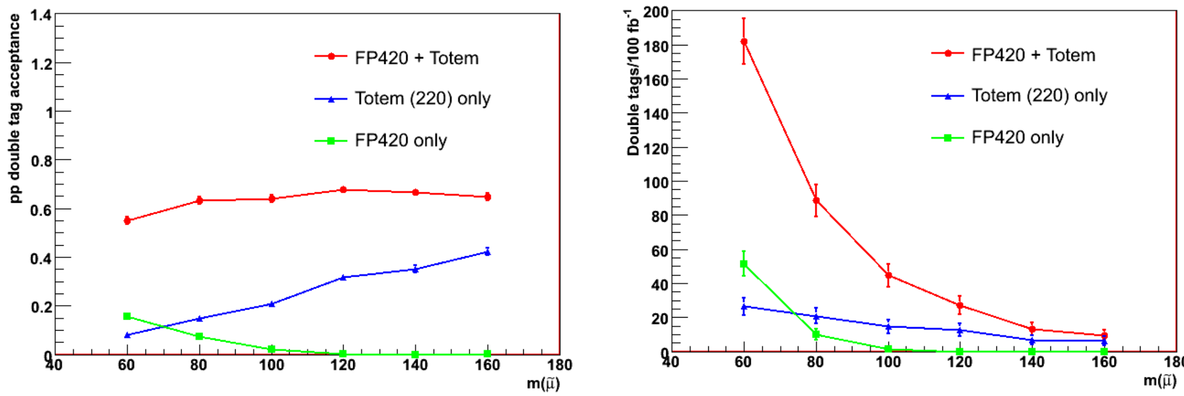

Figure 7: The proton tagging efficiency as a function of slepton mass on the left and the expected number of tagged events in 100 fb^{-1} on the right.

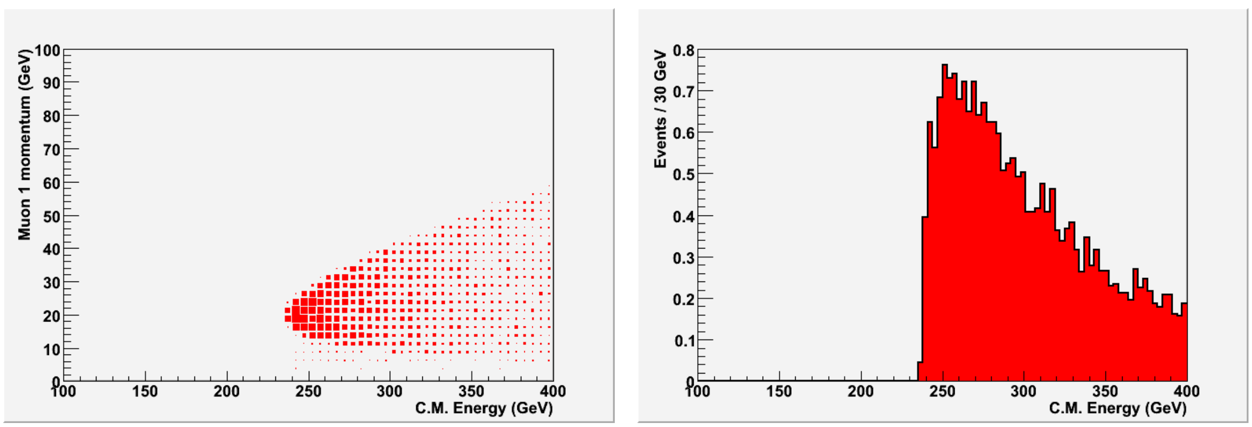

Figure 8: The reconstructed event variables after using the proton information to transform to the center of mass of the interaction. (Right) Center of mass energy for slepton events, (left) Center of mass energy versus muon 1 momentum. Slepton mass = 118 GeV

acceptance are shown in Table 1. The assumed distance of approach for the proton taggers is 3mm at 220m and 5mm at 420m. In scenarios 1 and 2 the efficiency for finding the offline muon pair with a double proton tag is high; in scenario 3, the low reconstruction efficiency is roughly compensated by the increased cross-section for lighter smuons. Since the reconstructed yields are small, it will be critical to keep the highest possible trigger efficiencies.

5 Triggering on $\gamma\gamma \to \tilde{\mu}^+\tilde{\mu}^-$

To evaluate the trigger performance the full simulation and trigger emulation is performed for the central detector, and ntuples are produced with the OpenHLT tools used in the CMS trigger studies group. For the forward protons, the Hector proton transport code has been integrated with OpenHLT to add the acceptance for the generator-level protons to the output. The CMS trigger [6] is composed of two stages; a fast decision

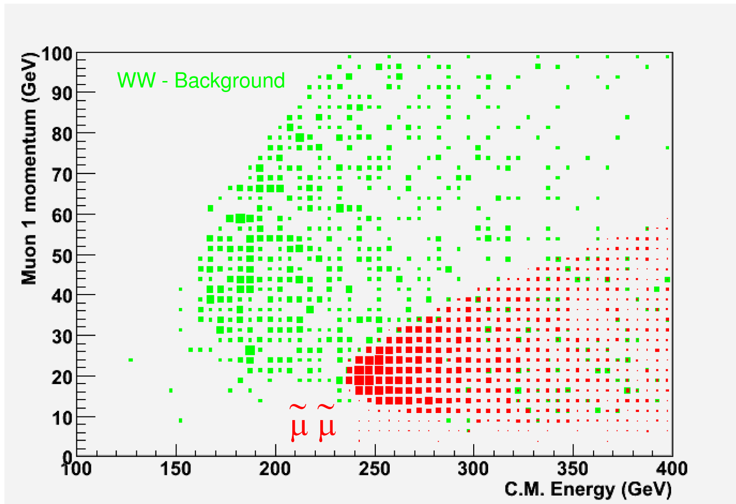

Figure 9: Comparison between irreducible WW background and slepton signal in center of mass versus muon momentum space. Slepton mass = 118 GeV

Quantity	Scenario 1	Scenario 2	Scenario 3
$m(\tilde{l})$(GeV)	118	118	82.5
$m(\chi_1^0)$(GeV)	98	112	77.5
σ (fb)	0.4	0.4	1.2
dimuon RECO eff.	78%	65%	26%
dimuon RECO eff. $\times$ p-tag acceptance	60%	50%	18%
Events/100 fb^{-1}	24	20	22

Table 1: $\gamma\gamma \to \tilde{\mu}^+\tilde{\mu}^-$ cross-section and offline efficiency for reconstructing two muons with two proton tags.

called L1 and a full reconstruction of the event called the High Level Trigger (HLT). A successful trigger will need to be highly efficient for the slepton events without being overwhelmed by extraneous background events. Both single and double muon events will be part of the standard triggers but muon momentum thresholds will be applied to bring the event rate down from the bunch crossing rate of 40Mhz to the 100Hz rate at which events can be selected and written to tape. The information from the forward proton detectors at 220 and 420 meters can be integrated with the HLT but due to limitations of speed-of-light and the latency of L1 only the detectors at 220m can reach the L1 trigger in time to be used.

We start by estimating the impact on the slepton event rates from the muon trigger thresholds. For each scenario we calculate the rate of events with two offline reconstructed (RECO) muons and two protons within the acceptance of the 220/420 meter proton detectors. We then calculate the efficiency reduction from; applying muon track quality cuts without a momentum threshold, applying the L1 muon threshold at HLT, and applying the standard HLT cut. For the muon trigger thresholds at high luminosity, we assume as a baseline the values used in the CMS PTDR [6]: 3 (14) GeV for L1 double (single) muon triggers, and 7 (19) GeV for HLT double (single) muon triggers. We consider both single and double muon triggers separately, and the OR of single and double muon triggers. The resulting trigger efficiencies are shown in Tables 2 - 4.

At the LM1 benchmark, the majority of events contain two high p_T muons, resulting in a high efficiency

L1	HLT	Scenario 1	Scenario 2	Scenario 3
3,3	none	93%	83%	69%
3,3	3,3	80%	62%	39%
3,3	7,7	76%	25%	8%

Table 2: Efficiency for double muon triggers, relative to events with two RECO muons and two proton tags.

L1	HLT	Scenario 1	Scenario 2	Scenario 3
14	none	92%	30%	17%
14	14	85%	17%	4%
14	19	71%	7%	1%

Table 3: Efficiency for single muon triggers, relative to events with two RECO muons and two proton tags.

L1	HLT	Scenario 1	Scenario 2	Scenario 3
14 OR 3,3	none	98%	87%	72%
14 OR 3,3	14 OR 3,3	94%	64%	40%
14 OR 7,7	19 OR 7,7	81%	26%	8%

Table 4: Efficiency for the OR of single and double muon triggers, relative to events with two RECO muons and two proton tags.

at HLT. In the two cases where the $l^{\pm} - \chi_1^0$ mass difference is small, less than one-quarter of the events that pass L1 and have two offline reconstructed muons will also pass the HLT with the nominal trigger thresholds. For example, in the second scenario, lowering the dimuon threshold to 3 GeV would result in more than a factor of 2 increase in trigger efficiency, while in scenario 3 the efficiency would increase by almost a factor of 5.

In both scenarios, the double muon trigger efficiencies are higher than those of the single muon triggers; using the OR of single and double muon trigger results in a small gain for scenarios 2 and 3, and a slightly larger gain in scenario 1. This is because the loss of efficiency at the trigger level is due both to the thresholds, and to the higher efficiency for low p_T muons that is possible with the offline *trackerMuons* algorithm. This is illustrated in Figures 10 - 12 by the muon p_T spectra seen at HLT and RECO for the two leading muons in events passing the L1 trigger.

5.1 Proton tagging in the trigger

The inclusion of forward proton information in the High Level Trigger allows the possibility of using the forward proton information to reduce the trigger thresholds in the central detector. The acceptance of the proton taggers depends on their distance of approach to the beam; we assume here a distance of 3mm for the 220m detectors, and 5mm for the 420m detectors.

5.2 Background

The trigger rate for low p_T muons is expected to be dominated by muons from heavy-flavor decays and K/π decays-in-flight. We estimate the dimuon background rate using a sample of muon-enriched Monte Carlo events, where at least one generator-level muon must have $p_T > 3$ GeV. The resulting effective cross-section for events passing the standard 3 GeV HLT dimuon trigger is $\sim$ 175 nb. Assuming an instantaneous luminosity of 2 x 10^{33} $cm^{-2}s^{-1}$ and a plausible HLT dimuon rate of $\sim$ 10 Hz a rejection factor of 35 must be achieved from the inclusion of forward proton information in order to keep the thresholds low.

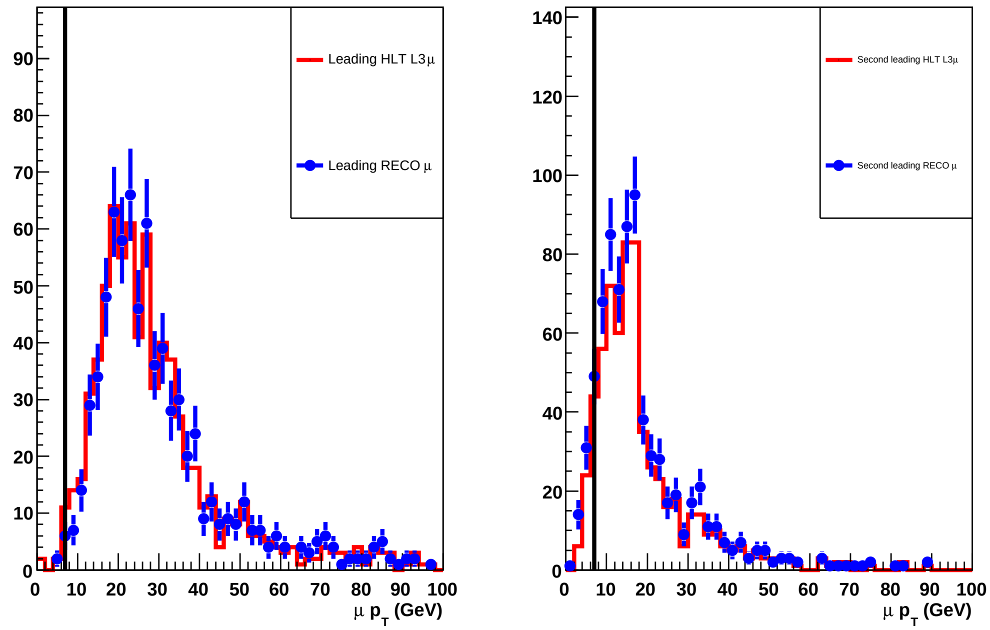

Figure 10: Leading and second leading muon at HLT (histograms) and RECO (points) in events passing the OR of the L1 single and double muon triggers in scenario 1.

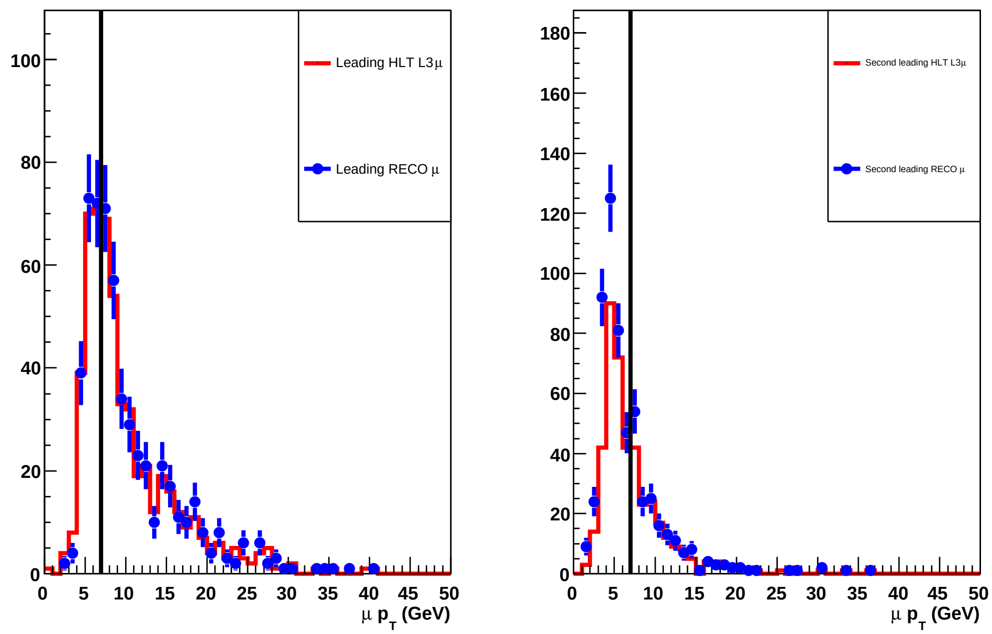

Figure 11: Leading and second leading muon at HLT (histograms) and RECO (points) in events passing the OR of the L1 single and double muon triggers in scenario 2.

5.2.1 Pileup and overlap backgrounds

At design luminosity the background from real events that produce a dimuon pair with two forward protons is small compared to overlap events. For a luminosity of 2 x 10^{33} $cm^{-2}s^{-1}$ and a total LHC cross-

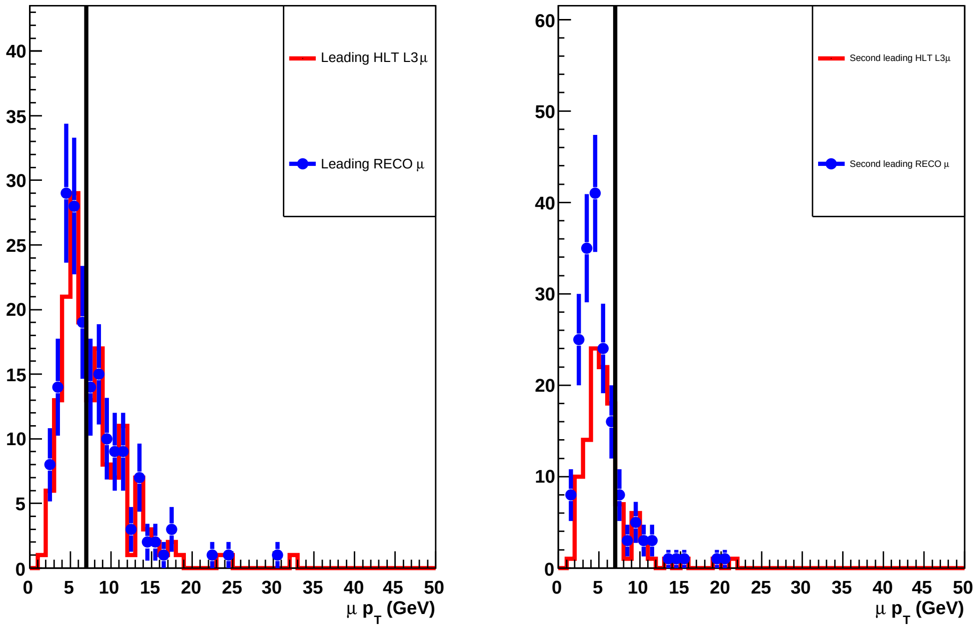

Figure 12: Leading and second leading muon at HLT (histograms) and RECO (points) in events passing the OR of the L1 single and double muon triggers in scenario 3.

section of 90 mb there will be on average $< 7 >$ interactions per bunch crossing. The dominant background comes from a random coincidence of three separate interaction within one bunch crossing. One event that produces a dimuon in the central detector and two others that each produce a forward proton. We use the PYTHIA Monte Carlo [7] to calculated the rate and energy distribution of forward protons from single diffractive events. At this luminosity there are 0.238 forward protons per bunch crossing. Using Poisson statistics we find the rate of seeing two forward protons in opposite directions is 0.023 / bunch crossing. If the forward proton detectors include time-of-flight detectors then the location along the beamline where the two protons would have originated can be calculated. We can then require the origin of the two muons to be consistent. Assuming a resolution of 20ps on the time-of-flight measurement only 1 in 24 dimuon events will have a position consistent with the proton time-of-flight. Therefore the fake rate will be 9.28 x 10^{-4} per dimuon. Adding the requirement of two forward protons to the HLT trigger will reduce the dimuon rate from $\sim$ 175 nb to $\sim$ 0.175 nb, easily within the ability of the trigger to write to tape. Given it's rate of 175 pb this will be a significant background to the slepton analysis but this background will have no structure in the three center of mass reconstruction variables.

5.3 Evaluating trigger performance in data

There are large theoretical uncertainties in the rates of diffraction and heavy-flavor muon production at the LHC. While the current studies are based entirely on MC, all aspects of the trigger strategy described here can be evaluated in real data. The dimuon trigger rate and its evolution with luminosity will be monitored beginning with the very early LHC data. The signal efficiency of the trigger will be evaluated using the known cross-section of the "standard candle" QED process $\gamma\gamma \to \mu^+\mu^-$ [8]. In addition, the proton taggers will allow complete reconstruction of the final state ($p\mu^+\mu^-p$) in these events. They can therefore be used to study the properties of pileup backgrounds in the data.

6 Conclusions

The combination of CMS with proton tracking detectors 220/420 meters from the CMS detectors offer a unique opportunity to study light non-Standard Model lepton production. In the case of SUSY, sleptons at the LM1 benchmark point will be triggered on with high efficiency, and can provide information on slepton and neutralino masses that is complementary to standard analyses. In cases where the slepton-neutralino mass difference is small, the information from the forward proton detectors will provide a handle to reduce the lepton trigger thresholds, increasing the efficiency for these events. In such scenarios, detection of slepton production may be difficult through conventional searches.

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