Two-Photon Exclusive Production of Supersymmetric Pairs at the LHC

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The two-photon production of charged supersymmetric pairs at the LHC has a unique signature of two leptons, large missing energy and two forward scattered protons. For low-mass supersymmetric scenarios, significant cross–sections are predicted for the MSSM. Proton kinematics information from very forward detectors (VFD) would allow for a precise mass reconstruction of right-handed sleptons and the LSP. For high luminosity runs, the probability to have accidental coincidence within central and very forward detectors increases although it can be reduced applying exclusivity conditions.

1 $\gamma\gamma$ physics at the LHC

In addition to the usual parton-parton interactions, a significant fraction of the *pp* collisions at the LHC will also involve photon-interactions. The available relative luminosity reaches 1% for photon-photon centre-of-mass energies $W_{\gamma\gamma} > 23$ GeV and still 0.1% for $W_{\gamma\gamma} > 225$ GeV [1]. Among the whole photon interactions at the LHC, the study of pair production of charged particles, including supersymmetric particles, is one of the most interesting cases since the QCD background is suppressed.

Exclusive two-photon interactions at the LHC provide clean detection conditions thanks to striking experimental signatures in absence of proton remnants: two very forward scattered protons, remaining intact after photon-exchange, and large rapidity gaps in the forward regions due to the exchange of a colorless object.

2 Detection of exclusive supersymmetric pairs

In $\gamma\gamma$ collisions, the production and decay mechanisms for low mass supersymmetry are simple and without decay chain problems. Also two-photon pair productions of left- and right-handed sleptons ($\tilde{e}_L^+$, $\tilde{\mu}_L^+$, $\tilde{e}_R^+$ $\tilde{\mu}_R^+$), staus ($\tilde{\tau}_1^+$, $\tilde{\tau}_2^+$), charginos ($\tilde{\chi}_1^+$, $\tilde{\chi}_2^+$) and charged Higgs bosons (H^+) have significant cross-sections of femtobarn-level. As an example for a low-mass supersymmetric scenario, the LM1 benchmark point in the mSugra theory [2] is used in the following discussion. The total cross-section for sparticle pair production is 2.23 fb in that specific model, the major contribution to signal being the two-photon production of scalars $\tilde{\ell}_R^+\tilde{\ell}_R^-$ ($m(\tilde{\ell}_R^+) =$ 118 GeV) and fermions $\tilde{\chi}_1^+\tilde{\chi}_1^-$ ($m(\tilde{\chi}_1^+) = 178$ GeV) as it is shown in Table 1. The Lightest

Supersymmetric Particle (LSP) is the first neutralino in that model ($m(\tilde{\chi}_1^0) = 96$ GeV). Details on model parameters and on mass spectrum can be found in [3].

Assuming a general multi-pupose LHC detector as CMS or ATLAS and full-set of dedicated very forward detectors to tag photon-interaction [4, 5], event selection requires very clean dileptonic final states:

- two isolated leptons of opposite charge,
- two scattered protons,
- large missing energy from the non-detection of ν and $\tilde{\chi}_1^0$,
- acoplanarity.

The only irreducible background process for this topology is the two-photon production of W pairs with fully leptonic decay. Indeed, two-photon production of lepton pairs $pp(\gamma\gamma \rightarrow \ell^+\ell^-)pp$ is easily suppressed using a cut on E_{miss} or accoplanarity. Exclusive WW production has a larger cross-section, around 108 fb.

Processes	σ [fb]	$\sigma_{acc}^{2p^+}$ [fb]	σ_{ana} [fb]
$\gamma\gamma \rightarrow \tilde{\ell}_R^+\tilde{\ell}_R^-$	0.798	0.445	0.357
$\gamma\gamma \rightarrow \tilde{\ell}_L^+\tilde{\ell}_L^-$	0.183	0.093	0.073
$\gamma\gamma \rightarrow \tilde{\tau}_i^+\tilde{\tau}_i^-$	0.604	0.001	0.001
$\gamma\gamma \rightarrow \tilde{\chi}_i^+\tilde{\chi}_i^-$	0.642	0.021	0.015
$\gamma\gamma \rightarrow H^+H^-$	0.004	/	/
$\gamma\gamma \rightarrow W^+W^-$	108.5	1.463	0.168

Table 1: Cross-sections of exclusive signal processes for production (σ), after applying central and forward detector acceptance cuts ($\sigma_{acc}^{2p^+}$) and after applying analysis cuts (σ_{ana}). '*acc*' includes same flavour leptons and τ-lepton tag; '*ana*' means $W_{miss} > 194$ GeV, $W_{\gamma\gamma} > 236$ GeV, $\Delta(\eta) < 2.1$, $\Delta(R) < 3.2$, $P_T^{miss} > 5$ GeV, $W_{lep} \notin [87\text{ GeV}; 95\text{ GeV}]$.

The two leptons must fall in the acceptance of the detector:

$$p_T(\mu^\pm) > 7 \text{ GeV}, \qquad p_T(e^\pm) > 10 \text{ GeV}, \qquad |\eta(\ell^\pm)| < 2.5 \tag{1}$$

while the protons are assumed to produce a hit in one very forward detector (VFD) if [6]:

$$\begin{aligned} 900 \text{ GeV} < E_\gamma < 120 \text{ GeV} \quad & \text{for 420m forward stations,} \\ 120 \text{ GeV} < E_\gamma < 20 \text{ GeV} \quad & \text{for 220m forward stations,} \end{aligned} \tag{2}$$

for a distance from the beam to the active edge taken as 4mm and 2mm respectively. An energy resolution $\sigma_{E_\gamma} = \max(\frac{E_\gamma}{100}, 1.5 \text{ GeV})$ is simulated on each detected proton.

Various possibilities to reduce the exclusive WW background based on kinematic variables are applied as cuts on the spatial distance ΔR, acoplanarity difference $\Delta\phi$, invariant dilepton mass W_{lep}, ... using the information of the central objects [3]. In case of low $\tan(\beta)$ models, another efficient way to reduce by a factor 2 the WW contribution is to select only same flavour dileptonic final states, as it is requested in this analysis. Also, lepton from tau decay can be tagged and rejected on a displaced vertex position veto.

The cross-sections after acceptance cuts (including same flavour requirement and τ-lepton tag) are 0.56 fb and 1.46 fb for the SUSY signal and the WW background respectively, as detailed in Table 1.

3 Precise mass reconstruction

The detection of the two scattered forward protons and the associated measurement of the photon energies give an unique and precise tool to reconstruct the initial conditions of the event. The two-photon invariant mass $W_{\gamma\gamma} = 2\sqrt{E_{\gamma_1} E_{\gamma_2}}$ and the missing mass W_{miss} (reconstructed

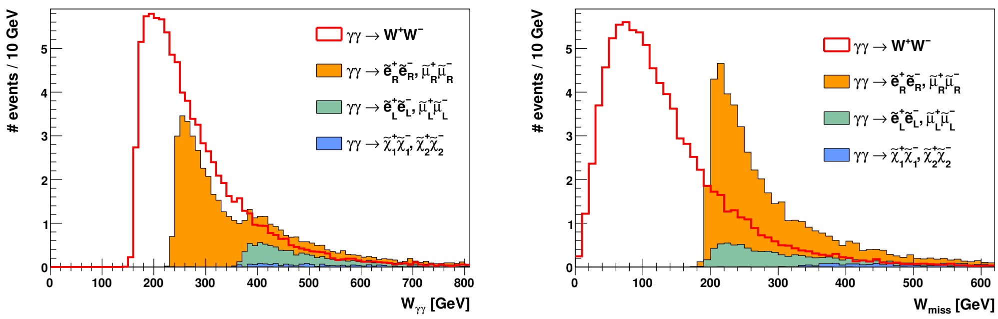

Figure 1: Distributions of the two-photon invariant mass $W_{\gamma\gamma}$ (left) and the missing mass W_{miss} (right) for the inetgarted luminosity L = 100 fb^{-1}. The background distribution of WW pairs is shown separately. Both are computed for events with 2 opposite charge same flavour leptons and 2 protons passing the acceptance cuts (1) and (2) only.

from $E_{miss} = E_{\gamma_1} + E_{\gamma_2} - E_{\ell_1} - E_{\ell_2}$ and similary for P_{miss}) distributions are shown in Figure 1, cumulatively for the signal, and separately for the background. The $W_{\gamma\gamma}$ distribution reflects the SUSY mass spectrum with two peaks due to the production thresholds of right slepton pairs (around 250 GeV) and left slepton pairs (around 400 GeV). Similary the W_{miss} distribution starts at about twice the mass of the LSP for the signal, whereas for the background the missing energy distribution starts at zero and peaks at around 70 GeV. Both distributions can be used to perform a mass edge study and extract the mass of $\tilde{\ell}^+_R$, $\tilde{\ell}^+_L$ and $\tilde{\chi}^0_1$. It should be stressed that the sleptons mass determination depends only on the VFD energy resolution and not on the ones for the central detectors. Also, since the energies and momenta of leptons are well reconstructed in the central detector, the uncertainty on the LSP mass determination is mainly dominated by photon energy resolutions.

Furthermore, combination of both information on the two-photon mass and the missing mass allows to measure the mass of the light $\tilde{\mu}_R$ and $\tilde{e}_R$ using the empirical quantity [3]:

$$(2m_{reco})^2 = W^2_{\gamma\gamma} - \left([W^2_{miss} - 4m^2_{\tilde{\chi}^0_1}]^{1/2} + [W^2_{lep} - 4m^2_{lep}]^{1/2}\right)^2 \quad (3)$$

The only input is this method is the mass value of the LSP, which can be taken from the mass edge study on W_{miss}. The distribution after an integrated luminosity of 100 fb^{-1} is shown on Figure 2. A narrow peak centered on $2 * m_{reco} = 236$ GeV $= 2 \times 118$ GeV, allows for an event-by-event determination of the $\tilde{e}^\pm_R$ and $\tilde{\mu}^\pm_R$ mass with few GeV resolution.

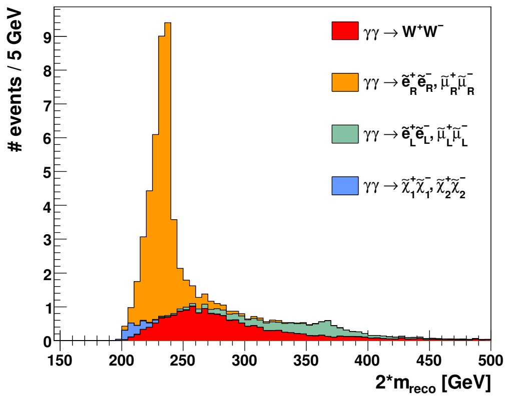

Figure 2: Cumulative distributions of the reconstructed mass $2 * m_{reco}$ for an integrated luminosity of L = 100 fb^{-1} assuming no pile-up.

4 Accidental coincidence background

In order to be sensitive to the femtobarn-level cross-sections of the exclusive SUSY pair production, this analysis has to be performed at designed LHC luminosity, when multiple interactions per bunch crossing (pile-up events) become significant. Assuming a total inelastic cross-section of 80mb and a collision frequency of 40 MHz, the number of overlap events per collision is distributed according to a Poisson distribution with

- for low luminosity $\mathcal{L} = 2 \times 10^{33} cm^{-2} s^{-1}$, $\langle N \rangle = 5.1$,
- for high luminosity $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$, $\langle N \rangle = 25.4$.

At these luminosities, the large number of overlap events leads to high probability to get accidental coincidence background when the dileptonic event detected in the central detector and the two forward proton detected in the VFD do not come from the same vertex [5, 7].

4.1 Accidental proton hits

The total inelastic cross section at the LHC is expected to be roughtly 80mb [8] with:

- Single diffraction:

Processes corresponding to $pp \rightarrow pX$ or $pp \rightarrow Xp$, simulated with MUSB(92) or MUSB(93) respectively in Pythia [9]. The associated cross-section is 14mb. Efficiencies to detect a scattered proton in a VFD are $\epsilon_{FP240} \simeq 15\%$ and $\epsilon_{F420} \simeq 12\%$. This is the dominant component of accidental proton hit for both distances.

- Double diffraction:

Processes corresponding to $pp \rightarrow XY$, simulated with MUSB(94) in Pythia. The associated cross-section is 10mb. Efficiencies to detect a scattered proton in a VFD are $\epsilon_{FP240} \simeq 1.3\%$

and $\epsilon_{FP420} \simeq 0$.

• Non-diffractive inelastic events:
Processes corresponding to $pp \rightarrow X$,simulated with MUSB(95) in Pythia (also called low p_T production). The associated cross-section is 55mb. Efficiencies to detect a scattered proton in a VFD are $\epsilon_{FP240} = 0.5\%$ and $\epsilon_{FP420} \simeq 0$.

Effect of multiple interactions per collision is simulated by superimposing N extra events, with N following the Poisson distribution, and distributing the vertices along a gaussian with 48.2mm width [10]. The associated probability to have two accidental proton hits per collision (one on each side of the interaction point) is calculated to be 1.16% for low and 21.54% for high luminosity on average.

4.2 Dileptons from inclusive processes

The considered inclusive processes with dileptonic final states, likely to mimic an exclusive SUSY signature if VFD hits match, are the inclusive $W^+W^- \rightarrow \ell^+\ell^-\nu$'s, $ZZ \rightarrow \ell^+\ell^- + jets$ and the Drell-Yan $Z/\gamma* \rightarrow \ell^+\ell^-$ processes, for which cross-sections for productions and after applying acceptance cuts (1) and (2) are quoted in Table 2 and have to be compared with numbers in Table 1 for the SUSY signal.

Processes		σ [fb]	$\sigma_{acc}^{2p^+}$ [fb]	$\sigma_{ana+excl}$ [fb]
WW^a	Low lumi	7.4×10^3	11.47	1.3×10^{-3}
	High lumi	”	213.23	24.0×10^{-3}
ZZ	Low lumi	1.1×10^4	10.64	0.4×10^{-3}
	High lumi	”	197.85	6.8×10^{-3}
$\gamma^*/Z^{a,b}$	Low Lumi	1.3×10^7	2.4×10^4	1.13
	High lumi	”	4.5×10^5	20.94

Table 2: Cross-sections of inclusive background processes for production (σ), after applying central and forward acceptance cuts ($\sigma_{acc}^{2p^+}$) and after applying analysis and exclusivity conditions ($\sigma_{ana+excl}$) (see section 5). MC generation cut : ^{a}: leptonic decay only; ^{b}: for $\sqrt{\hat{s}} > 14$ GeV. The conditions for 'acc' and 'ana' are the same as in Table 1. $excl$ means no extra track associated to the $\ell^+\ell^-$ vertex with $p_T > 0.5$ GeV.

As the dominant component is the inclusive Drell-Yan process, the analysis selection includes cuts on p_T^{miss} and on W_{lep}, both calculated from the lepton kinematic information in order to reduce the '$\gamma*$ part' and the 'Z part' of the spectrum respectively. We set $P_T^{miss} > 5$ GeV and $W_{lep} \notin [87 \text{ GeV}; 95 \text{ GeV}]$.

5 Exclusivity conditions

Accidental coincidence background, mainly composed by collisions with one inclusive Drell-Yan event and two single diffractive events, can be reduced at higher level trigger stage using kinematic constraints as consistency between the central and the forward systems in rapidity and mass. It can be further reduced using the fact that in general the number of tracks associated to the dilepton vertex is much smaller in exclusive events than in generic collisions.

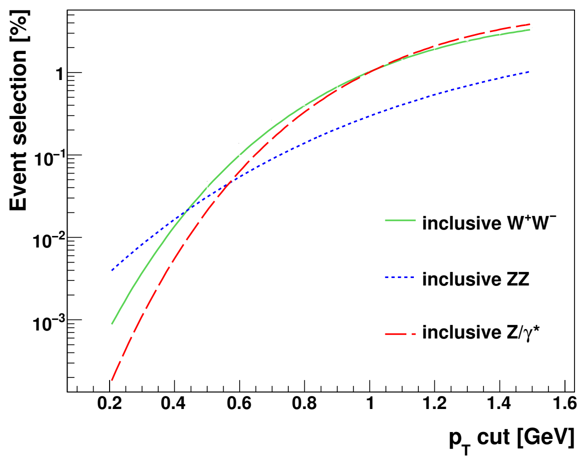

Figure 3: Background selection for 'no extra track with $p_T >$ p$_{T,cut}$' condition

For illustration, the inefficiency due to track-based exclusive conditions is shown in Figure 3 as a function of the minimum p_T value for track reconstruction. Using the high performance of the central tracking detector to reconstruct tracks even at low p_T [11], one can request an extra track with $p_T > 0.5$ GeV associated to the $\ell^+\ell^-$ vertex. This provides a reduction factor around 2500 for inclusive WW, 3000 for inclusive ZZ and 4500 for Drell-Yan production. However, it has to be emphasized that these reduction factor are strongly dependent on the Multiple Parton Interaction model used, and then have large uncertainty of factor 2.

The effect of the accidental coincidence background with track-based exclusivity conditions is shown in Figure 4 for low and high luminosities. For the lower one, the inclusive background remains at an acceptable level, so that $\tilde{e}_R^{\pm}$ and $\tilde{\mu}_R^{\pm}$ masses could still be reconstructed with a few GeV resolution. However, in case of high luminosity, the probability to have a central dileptonic event accidentally associated

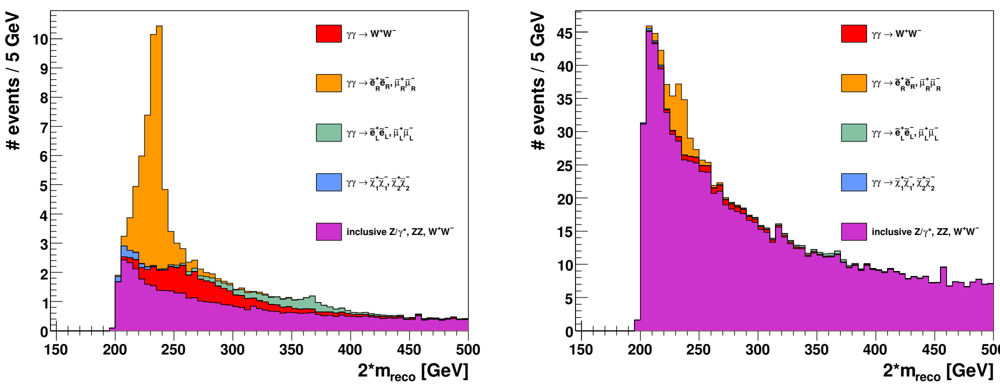

Figure 4: Cumulative distributions of the reconstructed mass $2 * m_{reco}$ for the integrated luminosity L = 100 fb^{-1} assuming low (left) and high (right) pile-up conditions. Track-based exclusivity conditions are applied.

to VFD hits is so large that the signal peak from exclusive supersymmetric pairs is hidden. In this context, precise time-of-flight detectors with few pico-second resolution have to be installed in association to the proton detector aiming to measure the relative time of arrival of protons in the VFD leg and reconstruct the proton-proton vertex [5, 12].

6 Conclusions

Photon-photon interactions provide novel, unique and complementary physics in the search of supersymmetric low mass models at the LHC, thanks to extra kinematical information obtained using the VFD. Even though the detection of low mass sparticles would be achieved earlier in nominal proton-proton collisions, the main interest lies in the capabilities for a reconstruction with a few GeV resolution of the LSP and the charged light scalars ($\tilde{e}_R$ and $\tilde{\mu}_R$) masses.

Unfortunately, in the harsh environment of the LHC, pile-up events will cause accidental coincidence background (an inclusive dilepton event associated to two accidental proton hits) which will degrade the SUSY detection potential.

At low luminosity, the use of strong track-based exclusivity conditions allows for a large reduction of the accidental background, and few GeV resolution on mass reconstruction is still expected. However, at high luminosity, the number of extra interactions per collisions is so high that no SUSY signal peak could be observed anymore. Fast timing detector, with $\mathcal{O}(10\text{ps})$ time resolution are then mandatory for the proton-proton vertices.

Acknowledgments

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