Search for Supersymmetry at CMS in Events with Two Photons and Missing Transverse Energy at $\sqrt{s} = 13$ TeV (**CADI:SUS-15-012**)

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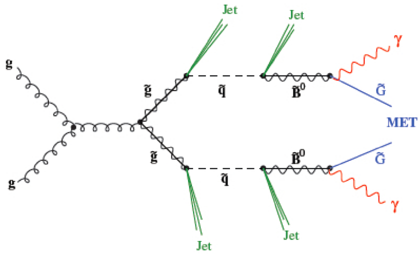
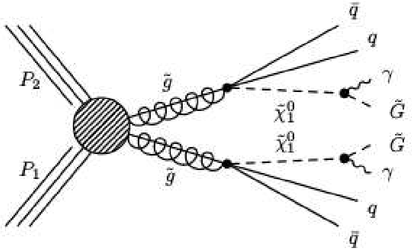
Supersymmetry (SUSY) and Gauge Mediated Supersymmetry Breaking (GMSB):

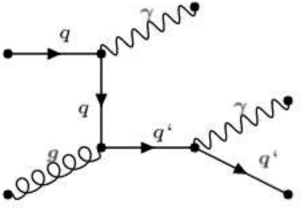
- Symmetry between SM bosons and fermions to supersymmetric fermions and bosons.
- Broken symmetry: otherwise the SM particle and its SUSY partner would have the same mass
  - GMSB:
    - Ordinary gauge interaction is responsible for SUSY breaking.





Search Strategy: Backgrounds

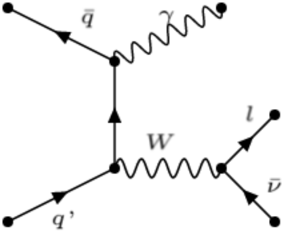
- Quantum Chromodynamics (QCD) background
  - May have two real photons in the final state, or one or both coming from the electromagnetically-rich jet fragmentation mimicking the response of a photon.
  - Missing transverse energy (E_T^{miss} or MET) from object mis-measurement.



QCD Background

Most significant background as the QCD cross-section is enormous!

- Electroweak (EWK) background
  - SM process with neutrino in the final state.
  - $W\gamma$, W-jets events where $W \to e\nu$ etc.



EWK Background

genuine E_T^{miss}, but very small background.

  - Other negligible contributions: $Z\gamma\gamma \to \nu\nu\gamma\gamma$, $W\gamma\gamma \to l\nu\gamma\gamma$, $t\bar{t}\gamma\gamma$.

Relevant Object Reconstruction:

Candidate (Double Photon, $\gamma\gamma$) Sample

- Define $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$
- Hadronic energy deposition (H)/ electromagnetic energy deposition(E) < 0.05 around the photon object.
- Showershape in η direction should be consistent with electromagnetic shower.
- No hit in inner two layers of silicon pixel detector.
- The selected objects should be well isolated. Applied particle-flow based isolation.
- The photon selection follows medium cut based photon Id.

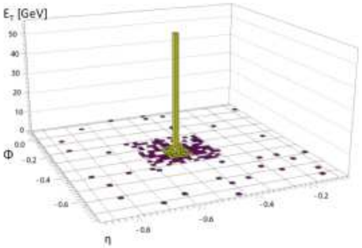


Figure : A sample photon deposition in the detector.

Control samples and Trigger:

Control samples for QCD background estimation

- **Electron (ee) Sample**
  - Selection of electron: same as photon selection but requires hit in the silicon pixel detector.
  - Two separated electrons having invariant mass within 75 to 105 GeV (wihin Z boson mass).
- **Fake (ff) Sample**
  - Comes primarily from electromagnetically rich jets whose fragmentation mimic the response of photons.
  - The requirement of deposited transverse momenta by charged hadrons around the object within $\Delta R < 0.3$ or the showershape in η direction (but **NOT** both) is orthogonal to that of photon selection.
- These samples don't have real E_T^{miss}, ideal for QCD background modeling.

Control sample for EWK background estimation:

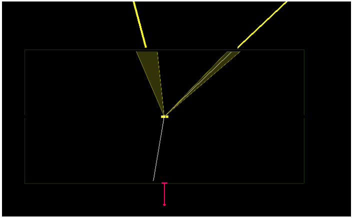
- **Electron-Photon ($e\gamma$) sample:** events with one electron and one photon.
- Real E_T^{miss}.

High Level Trigger:

- Two objects with leading object $p_T > 30$ GeV and sub-leading object $p_T > 18$ GeV.
- Showershape for each object must be less than 0.015 for the barrel and also H/E< 0.1.
- The objects should be isolated.
- Invariant mass > 95 GeV.

Missing Transverse Energy (E_T^{miss} or MET):

- Imbalance in the total transverse momentum of particles before and after collision.
  - May be due to object mis-measurement.
  - Particles leaving the detector undetected.



Definition

$\vec{E_T^{miss}} = -\sum_{i=1}^{n} \vec{p_{Ti}}$ where i runs over all visible particles in the event.

E_T^{miss}

Toughest thing to measure because it involves resolution of all the visible particles!

- Correction to E_T^{miss}:
  - Type 0 correction: correction on E_T^{miss} to reduce the effect of pileup.
  - Type 1 correction: the propagation of correction applied to the jets.

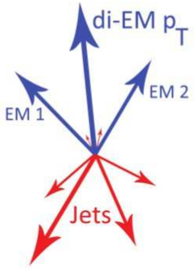
Double-Photon Sample

- Any double-photon sample selected will invariably contain jet-jet, photon-jet samples because of jet fluctuations appearing as photons.

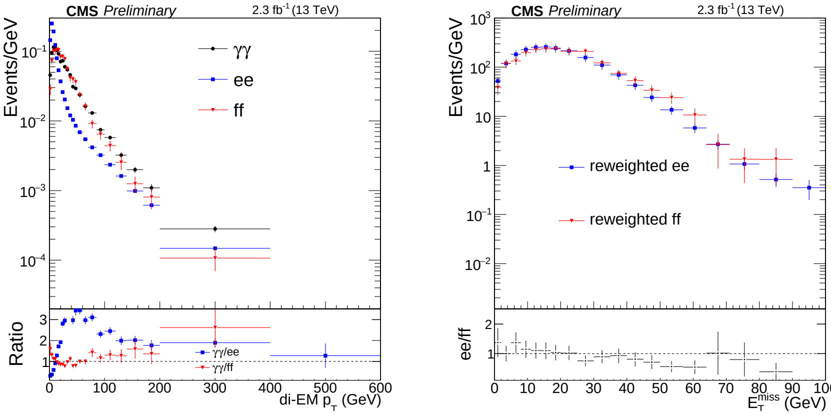
- Very tough to simulate the E_T^{miss} distribution when jets fluctuate and appear as photons, as resolution in measuring jets are poor.
- Even with events with two true photons, mis-measurement of the E_T^{miss} possible due to the additional hadronic activity.
- Data-driven technique: control sample with *ee* and *ff* because they don't have real E_T^{miss}.
- Control samples differ from candidate samples in hadronic activity.

di-EM p_T:

- di-EM p_T is defined as transverse momenta of two electromagnetic objects: $\vec{p_T}^{di-EM} = (\vec{p_T}_1 + \vec{p_T}_2)$ where $\vec{p_T}_1$ and $\vec{p_T}_2$ are the individual transverse momentum of the electromagnetic objects.
- This is a measure of hadronic recoil in the sample.

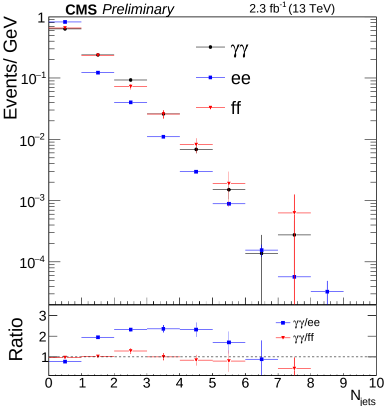


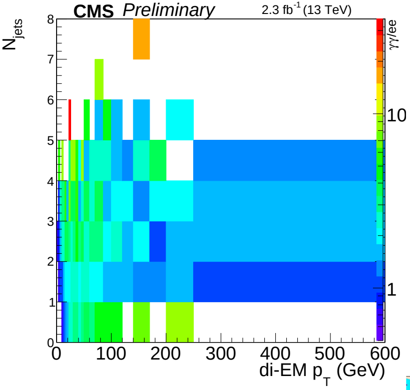
Modeling QCD Background: Di-EM p_T Reweighting



- The primary QCD background estimate comes from the double electron sample.
- The prediction from double fake samples used to cross check our double electron estimate.

- E_T^{miss} distribution between control and candidate samples can differ because of difference in jet multiplicity.
- The energy resolution in an event where there are three jets having total p_T of 100 GeV will be worse than that of an event where there is only one jet having p_T of 100 GeV.
- To extract any dependence of jet multiplicity with di-EM p_T for ee sample, the jet multiplicity is plotted in bins of di-EM p_T.

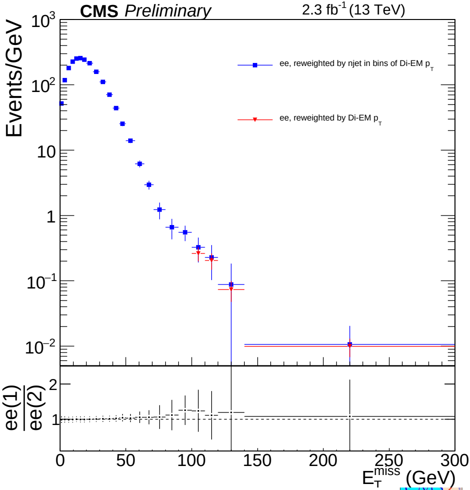




Effect of reweighting by jet multiplicity distribution:

- To know the effect of jet multiplicity reweighting, we plot only di-EM p_T reweighted ee E_T^{miss} and jet multiplicity in bins of di-EM p_T reweighted ee E_T^{miss}.
- The ratio shows the effect of jet multiplicity reweighting is small.
- Take the difference between only di-EM p_T reweighted ee E_T^{miss} and jet multiplicity in bins of di-EM p_T reweighted ee E_T^{miss} as one of our systematic uncertainties.

E_T^{miss} bin (GeV)	Expected QCD (from reweighted *ee*)
$100 - 110$	1.85 ± 0.96
$110 - 120$	1.53 ± 0.63
$120 - 140$	0.97 ± 0.62
> 140	0.61 ± 2.15

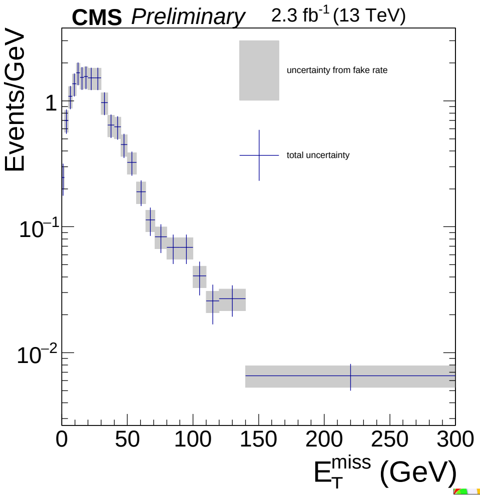


EWK Background:

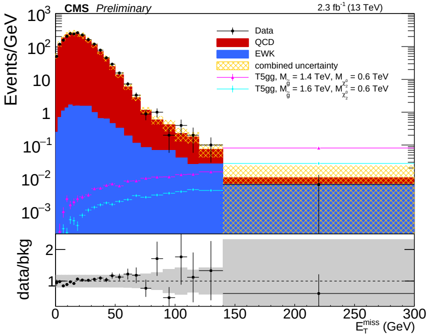
- Coming mainly from $W\gamma$ sample where $W \to e\nu$ and electron is misidentified as photon, so we get double-photon final state.

- To model the EWK background, need to find the electron-to-photon misidentification rate (fake rate) ($f_{e\to\gamma}$) and scale the electron-photon E_T^{miss}distribution with it.
- $f_{e\to\gamma} = 0.021 \pm 0.002$
- $N_{\gamma\gamma} = \frac{f_{e\to\gamma}}{1-f_{e\to\gamma}} N_{e\gamma}$
- $M_{e\gamma} > 105$ GeV.

E_T^{miss}bin (GeV)	Expected EWK
$100 - 110$	0.41 ± 0.12
$110 - 120$	0.26 ± 0.09
$120 - 140$	0.54 ± 0.15
> 140	1.03 ± 0.25



Analysis Technique: E_T^{miss} Plot with Candidate and Modeled Background



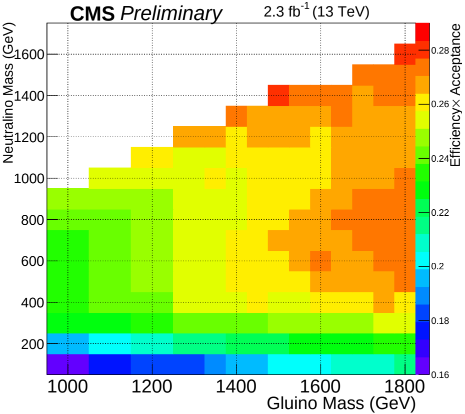
E_T^{miss} bin (GeV)	Expected QCD+EWK	Observed
100 – 110	2.26 ± 0.96	4
110 – 120	1.79 ± 0.64	2
120 – 140	1.51 ± 0.64	2
$>$ 140	1.64 ± 2.16	1

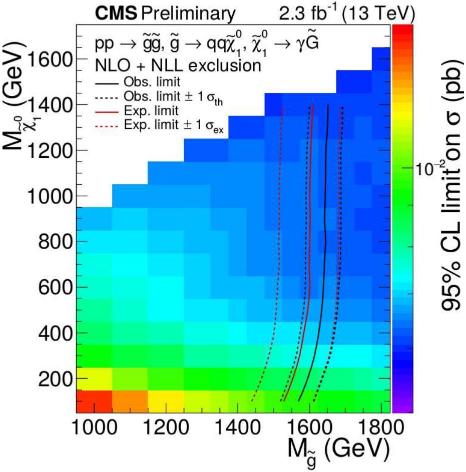
Table : Expected and observed events for $E_T^{miss} > 100$ GeV

Remark:

- Did not get significantly excess events over expected background in data.
- Put the limits on production cross sections.

Setting the limits:





- Efficiency×Acceptance is low for low gluino and neutralino masses, as here most of the photons fail to pass $p_T > 40$ GeV cut.

Conclusion:

- Full analysis done on 13 TeV data.
- Successfully modeled the background for the analysis.
- Did not observe any significantly excess event in the signal region.
- The analysis with 8 TeV data (integrated luminosity 19.6 fb^{-1}) set limits on gluino mass at 1.35 TeV (arxiv:1507.02898). With only 2.3 fb^{-1} of 13 TeV data, the limits on gluino mass is extended to 1.65 TeV.

- Thank You!

- Back Up

Trigger:

- Primary analysis trigger: *HLT_Diphoton30_18_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass95_v**.
- Lead photon $p_T > 30$ GeV and trail photon $p_T > 18$ GeV.
- Leading leg has $L1$ seed, but sub-leading leg is unseeded.
- $M_{\gamma\gamma} > 95$ GeV.
- Photons must pass *_HE_R9Id_* and (*_R9Id_* or *_IsoCaloId_*).

*_R9Id_*	$R9 > 0.85$
*_IsoCaloId_*	$\sigma_{i\eta i\eta} < 0.015$ ECAL Isolation $< (6 + 0.012 \times p_T^{\gamma})$ Track Isolation $< (6 + 0.002 \times p_T^{\gamma})$
*_HE_R9Id_*	H/E< 0.1 R9 > 0.5

High Level Trigger

1. *HLT_Diphoton30_18_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass95_v**
2. *HLT_Diphoton30_18_R9Id_OR_IsoCaloId_AND_HE_R9Id_DoublePixelSeedMatch_Mass70_v**
3. *HLT_Diphoton30PV_18PV_R9Id_AND_IsoCaloId_AND_HE_R9Id_DoublePixelVeto_Mass55_v**
4. *HLT_Diphoton30EB_18EB_R9Id_OR_IsoCaloId_AND_HE_R9Id_DoublePixelVeto_Mass55_v**

Trigger efficiencies:

- Trigger requires two photons passing sub-leading filters and one photon passing leading filters.
- Total trigger efficiency $\epsilon_{tot} = \epsilon_{lead,lead} \times \epsilon_{lead,sub} \times \epsilon_{sub,sub}$
- $\epsilon_{lead,lead}$ means efficiency of leading photon passing leading filter.
- $\epsilon_{lead,sub}$ means efficiency of leading photon passing sub-leading filter.
- $\epsilon_{sub,sub}$ means efficiency of sub-leading photon passing sub-leading filter.

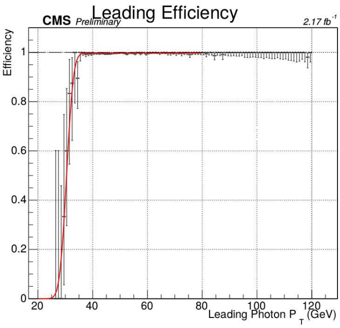


Figure : Efficiency of leading photon passing leading filter as function of photon p_T

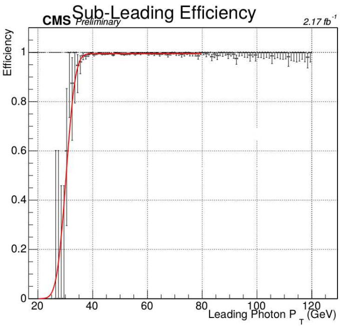


Figure : Efficiency of leading photon passing sub-leading filter as function of photon p_T

Trigger efficiencies: Sub-leading photon

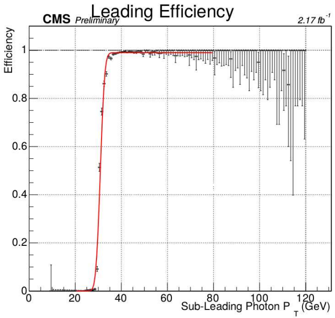


Figure : Efficiency of sub-leading photon passing leading filter as function of photon p_T

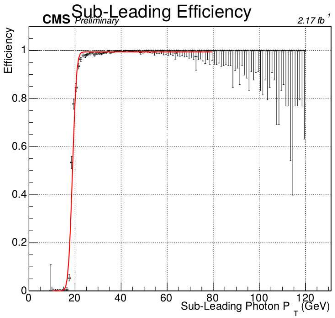


Figure : Efficiency of sub-leading photon passing sub-leading filter as function of photon p_T

- We use the photon p_T cut at 40 GeV.
- At this point, $\epsilon_{lead,lead} = 0.997$, $\epsilon_{lead,sub} = 0.995$
- $\epsilon_{sub,sub} = 0.994$, $\epsilon_{tot} = 98.6\%$

Photon selection efficiency: Tag and Probe

- Determine the ID efficiency of $e\gamma$ objects.
- Photon efficiency $\epsilon_\gamma = \epsilon_\gamma^{MC} \times \frac{\epsilon_e^{data}}{\epsilon_e^{MC}}$
- Computed the efficiency as a function of kinematic variables like: E_T, $|\eta|$, $\Delta R(\gamma, jet)$.
- Data used: DoubleEG streams (Run C and Run D)
- Trigger used: $HLT\_Diphoton30\_18\_R9Id\_OR\_IsoCaloId\_AND\_HE\_R9Id$ $\_DoublePixelSeedMatch\_Mass70\_v*$
- MC sample: DY→ee sample ($DYToEE\_13TeV - amcatnloFXFX - pythia8$)
- γ selection:
  - $|\eta| < 2.5$, $E_T > 25$ GeV for probe, $E_T > 35$ GeV for tag
  - tagged photon passes tight photon selection
  - probe efficiencies were computed for loose, medium and tight selections.

Scale factors:

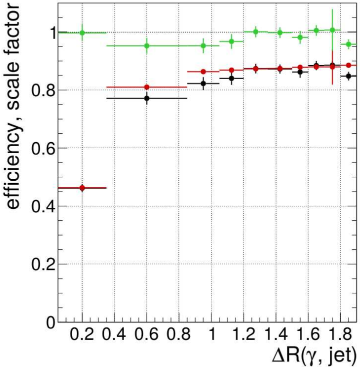


Figure : efficiency vs $\Delta R(\gamma, jet)$ (data, MC, scale factor)

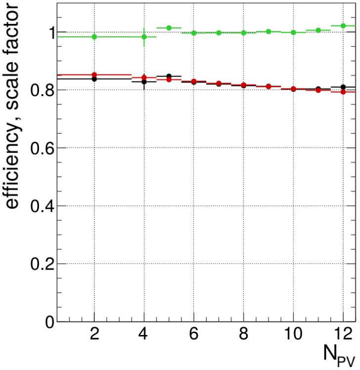


Figure : efficiency vs N_{PV}, (data, MC, scale factor)

- Overall scale factor $= 0.985 \pm 0.011$ (Official values: 0.983 ± 0.012).

Cross check on pure QCD background estimate:

- Fake samples are sideband to candidate sample.
- If there is no signal anywhere in the E_T^{miss}, expect the relative fraction of candidate and fake-fake sample should remain constant as a function of E_T^{miss}.
- We fit the $\gamma\gamma$/ff ratio with a simple function (in the form exp(ax+b)) in the control region ($E_T^{miss} < 100$ GeV).
- Extend this ratio in signal region and ratio$\times$ ff in one bin gives the double photon estimate coming from pure QCD in that bin.
- We take the overall normalization from fake sample and the distribution from loose fake samples.

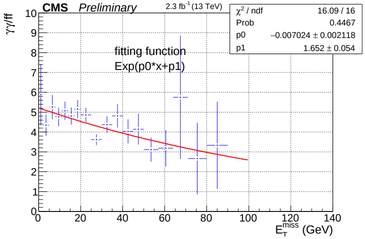
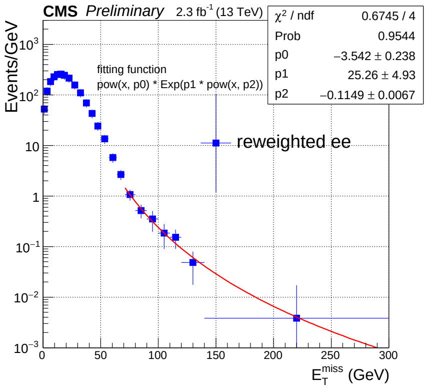


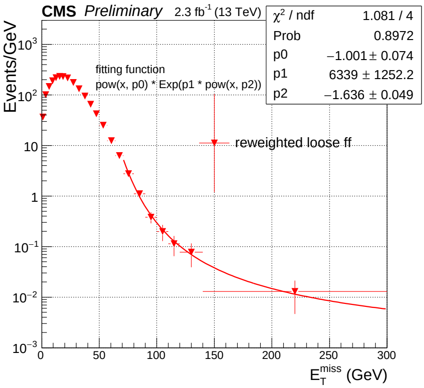
Table : Estimation of QCD background for $E_T^{miss} > 100$ GeV using the *ff* control sample

E_T^{miss} bin (GeV)	Method	Value
100 – 110	Di-EM p_T reweighting method	1.97 ± 0.69
	$\gamma\gamma/ff$ ratio method	1.12 ± 0.59
110 – 120	Di-EM p_T reweighting method	1.12 ± 0.48
	$\gamma\gamma/ff$ ratio method	0.61 ± 0.35
120 – 140	Di-EM p_T reweighting method	1.53 ± 0.76
	$\gamma\gamma/ff$ ratio method	0.68 ± 0.43
$>$ 140	Di-EM p_T reweighting method	2.05 ± 1.32
	$\gamma\gamma/ff$ ratio method	0.91 ± 0.70

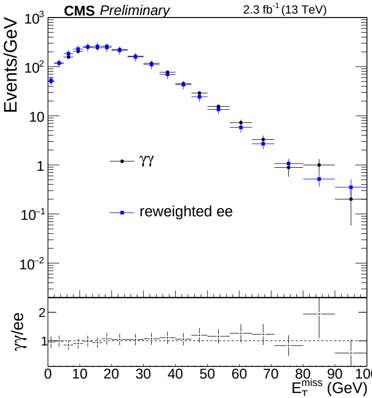
Shape difference between ee and ff E_T^{miss} distribution:

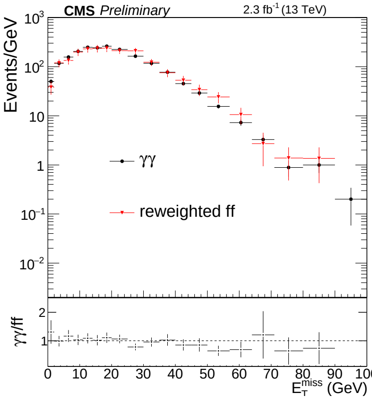
- Fit reweighted ee and ff E_T^{miss} distribution with $x^{p_0} \times exp(p_1 \cdot x^{p_2})$, where p_0, p_1 and p_2 are obtained from the fit in the range 70-300 GeV.
- Integrate each of the fits in the signal bins.
- Take the difference between the integrated results in each bin between ee and ff.
- Uncertainty in the last bin is large because here the integration range is high.





Comparison of reweighted control samples and data E_T^{miss}





Uncertainty in QCD background estimation:

Table : Shape uncertainty coming from the difference between the *ee* and *ff* E_T^{miss}distributions for $E_T^{miss} > 100$ GeV

E_T^{miss}bin (GeV)	*ee* prediction	*ff* prediction	difference	fractional difference
100 – 110	1.87	2.21	0.34	18.18%
110 – 120	1.16	1.30	0.14	12.07%
120 – 140	1.25	1.43	0.18	14.40%
$>$ 140	1.39	3.48	2.09	150.36%

Table : Systematic and Statistical Uncertainties from QCD Background Estimation

E_T^{miss}bin (GeV)	Systematic Uncertainty	Value
100 – 110	Di-EM p_T reweighting	15.11%
	Jet multiplicity reweighting	33.77%
	Shape difference between *ee* and *ff*	18.18%
	Statistical uncertainty of *ee* sample	30.81%
110 – 120	Di-EM p_T reweighting	16.60%
	Jet multiplicity reweighting	14.87%
	Shape difference between *ee* and *ff*	12.07%
	Statistical uncertainty of *ee* sample	33.33%
120 – 140	Di-EM p_T reweighting	33.31%
	Jet multiplicity reweighting	29.39%
	Shape difference between *ee* and *ff*	14.40%
	Statistical uncertainty of *ee* sample	41.75%
140 – *Inf*	Di-EM p_T reweighting	39.37%
	Jet multiplicity reweighting	20.34%
	Shape difference between *ee* and *ff*	150.36%
	Statistical uncertainty of *ee* sample	70.98%

Other sources of systematic uncertainties:

Table : Summary of systematic uncertainties included in the determination of the expected exclusion contours.

Systematic Uncertainty	[%]
Integrated luminosity	4.6
Photon Data/MC scale factor	2.4
Jet energy scale	0 - 23
Finite MC statistics	0 - 16
PDF error on cross section	13 - 22

Muon

- $p_T > 30$ GeV.
- $|\eta| < 1.4442$.
- passes medium Id.

Table : Muon Medium Id

1. Global muon Normalized global-track χ^2 Tracker-Standalone position match Kick finder Segment compatibility	normalized $\chi^2 < 3$ χ^2 LocalPosition < 12 track Kink < 20 > 0.303
2. Tight segment compatibility	> 0.451

Jets

- $p_T > 30$ GeV and $|\eta| < 2.4$.
- Passes PFLooseId.
- Separated by $\Delta R > 0.4$ from all electrons, photons and muons.

Photon

- $p_T > 40$ GeV
- Restricted to barrel region.
- passes medium Id.
- pixel seed $= 0$.

Electron

- Identical to photon selection except pixel seed match.

Table : 25 ns Spring 15 Cut-based Medium Photon Id

H/E	0.05
$\sigma_{i\eta i\eta}$	0.0102
ρ corrected charged hadron isolation	1.37
ρ corrected neutral hadron isolation	$1.06 + 0.014 \times p_T + 0.000019 \times p_T^2$
ρ corrected photon isolation	$0.28 + 0.0053 \times p_T$

Fake selection:

Fake sample

- $p_T > 40$ GeV
- $|\eta| < 1.4442$
- $H/E < 0.05$
- Photon isolation and neutral hadron isolation from ID applied
- Passes pixel seed veto
- $R9 < 1.0$ and $\sigma_{i\eta i\eta} > 0.005$ to avoid spikes
- $0.0102 < \sigma_{i\eta i\eta} < 0.015$ XOR $1.37 <$ Charged Isolation < 15.0

Loose Fake sample

- $p_T > 40$ GeV
- $|\eta| < 1.4442$
- $H/E < 0.05$
- Photon isolation and neutral hadron isolation from ID not applied
- Passes pixel seed veto
- $R9 < 1.0$ and $\sigma_{i\eta i\eta} > 0.005$ to avoid spikes
- $0.0102 < \sigma_{i\eta i\eta} < 0.020$ OR $1.37 <$ Charged Isolation < 40.0

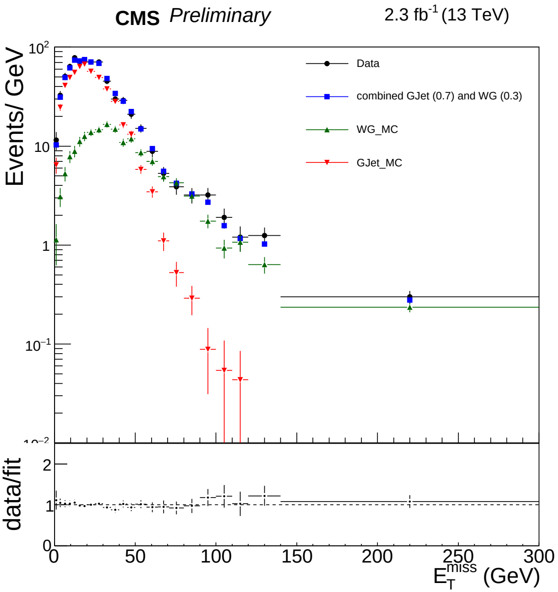
Subtraction of other contributions in control region:

- $t\bar{t}$ sample where top decays leptonically:
  - Will have two electrons and E_T^{miss} due to neutrino.
  - In our ee control sample, we found 17.27 ± 0.98 events in the signal region from $t\bar{t}$.
  - We subtracted it's shape.
- $Z + jets$ sample where $Z \to \nu\nu$
  - In tight fake sample, we found only 0.1 events in the signal region. We neglected this.
  - In loose fake sample, we found 15.8 ± 0.9 events in the signal region. We also subtracted this shape.

Fake rate calculation:

- We find the number of observed $Z \to ee$ events in the ee mass spectrum as given by $N_{ee} = (1 - f_{e\to\gamma})^2 N_{trueZ}$ where N_{trueZ} is the true number of $Z \to ee$ events.
- the observed $Z \to ee$ peak in the $e\gamma$ mass spectrum is given by $N_{e\gamma} = 2[f_{e\to\gamma}(1 - f_{e\to\gamma})]N_{trueZ}$.
- We used single electron trigger: HLT_Ele27_eta2p1_WPLoose_Gsf
- The factor of 2 comes because we do not distinguish between $e\gamma$ events where electron has higher p_T compared to photon and vice versa.
- $f_{e\to\gamma} = N_{e\gamma}/(2N_{ee} + N_{e\gamma})$
- The number of events from the $e\gamma$ mass spectrum is given by $N_{e\gamma} = (1 - f_{e\to\gamma})N_{trueW}$ where N_{trueW} is the true $W\gamma$ events.
- Then in the $\gamma\gamma$ sample, the number of $N_{\gamma\gamma}$ coming from W background is given as: $N_{\gamma\gamma} = f_{e\to\gamma}N_{trueW} = N_{e\gamma}f_{e\to\gamma}/(1 - f_{e\to\gamma})$.

EWK Components:

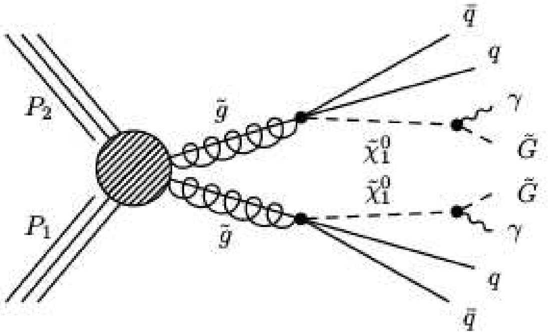


Effect of different cuts on signal point (1600, 800)

- total events: 13852
- events having two photons ($p_T > 0, 0$) : 3960
- events having two photons ($p_T > 30, 18$) : 3477
- events having two photons ($mass > 95$) : 3508
- events having two photons ($mass > 95, p_T > 30, 18$) : 3461
- events having two photons ($mass > 105, p_T > 30, 18$) : 3454
- events having two photons ($mass > 105, p_T > 40, 40$) : 3435

Simplified model:

- a limited set of hypothetical particles and decay chains are introduced
- this is to produce a given topological signature such as the diphoton final state studied in this analysis
- For gluino mass of 1.6 TeV and neutralino mass of 600 GeV, the event yield in the signal region: 4.58 and last bin is 4.41.



Standard Model Production:

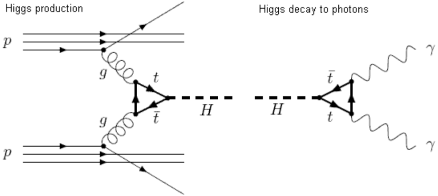


Figure : Higgs Boson decaying to two photons

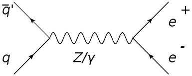


Figure : Z boson decaying to electrons

Standard Model Wγ production, Feynman Diagrams: