A Search for Supersymmetry Using Events with Photons and Large Missing Transverse Energy at CMS

Rachel Yohay
University of Virginia
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on behalf of the CMS collaboration
Outline

• Introduction
  • Gauge-mediated SUSY searches with photons
  • Next-to-lightest superpartner (NLSP) type → final state
  • 3 complementary searches
• Physics object selection in CMS
  • Photons
  • Jets and missing transverse energy ($E_T^{miss}$)
  • Leptons
• Event selection
• Backgrounds
• Results
• Interpretation in terms of simplified SUSY models
• Conclusions
**Gauge-mediated SUSY searches with photons**

**ALEPH DELPHI L3 OPAL**

\[ c^+c^- \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow \tilde{g}\tilde{g} \]

130GeV \(\pm\) 209 GeV

Excluded at 95% C.L.

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- Minimal GMSB model (SPS8) [2]
- Neutralino pair production
- \(m_{\text{neutralino}} > 97\ \text{GeV}\) for short-lived neutralino

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**Tevatron Run II (2001-2010)**

- Minimal GMSB model (SPS8) [2]
- Chargino and neutralino pair production
- \(m_{\text{neutralino}} > \sim 170\ \text{GeV} (\Lambda > 124\ \text{TeV})\) for short-lived neutralino

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**LHC7 (2009-2011)**

- General model parametrized in terms of \(\tan \beta\) and squark, gluino, and wino/bino/higgsino masses
- No assumptions on the number of messengers, the messenger mass, or the SUSY breaking scale
- Squark and gluino production
- Short-lived neutralino

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R. Yohay  
SUSY11 August 30, 2011  
3
GGM final states

**2γ+jets+MET**

Bino NLSP: neutralino(bino) → γ+gravitino

**1γ+jets+MET**

Wino NLSP: neutralino(wino) → γ+gravitino and chargino(wino) → W(→ lv)+gravitino

**γ+jets+MET**

Bino NLSP: neutralino(bino) → γ+gravitino or neutralino(bino) → Z(→ jets)+gravitino

Wino NLSP: neutralino(wino) → γ+gravitino and chargino(wino) → W(→ jets)+gravitino
3 complementary searches

Search #1: 2 photons + ≥1 jet + ME_T (bino NLSP)  

Search #2: photon + lepton + ME_T (wino NLSP with leptonic W decays)  

Search #3: photon + ≥3 jets + ME_T (bino NLSP, wino NLSP)
Physics object selection in CMS

- Isolated leptons
  - Electrons
    - Inconsistent with ECAL noise
    - Inconsistent with photon conversion
  - Muons

- Isolated photons
  - Inconsistent with ECAL noise
  - No matching hit pattern in the silicon pixel detector

- Jets and $\mathbb{M}$
  - Anti-$k_T$ algorithm with $R = 0.5$
  - Inconsistent with ECAL and HCAL noise
Event selection

- Using the CMS reconstructed physics objects, build 3 different event selections corresponding to the 3 GGM topologies

<table>
<thead>
<tr>
<th>Topology</th>
<th>No. isolated photons</th>
<th>No. isolated leptons (e or μ)</th>
<th>No. jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double photon</td>
<td>≥2 with:</td>
<td>No requirement</td>
<td>≥1 with:</td>
</tr>
<tr>
<td></td>
<td>• Leading $E_T &gt; 45 \text{ GeV}$</td>
<td></td>
<td>• $E_T &gt; 30 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>• Trailing $E_T &gt; 30 \text{ GeV}$</td>
<td></td>
<td>•</td>
</tr>
<tr>
<td></td>
<td>• $</td>
<td>\eta</td>
<td>&lt; 1.4442$</td>
</tr>
<tr>
<td>Photon + lepton</td>
<td>≥1 with:</td>
<td>≥1 with:</td>
<td>No requirement</td>
</tr>
<tr>
<td></td>
<td>• $E_T &gt; 30 \text{ GeV}$</td>
<td>• $E_T &gt; 20 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• $</td>
<td>\eta</td>
<td>&lt; 1.4442$</td>
</tr>
<tr>
<td>Single photon</td>
<td>≥1 with:</td>
<td>No requirement</td>
<td>≥3 with:</td>
</tr>
<tr>
<td></td>
<td>• $E_T &gt; 75 \text{ GeV}$</td>
<td></td>
<td>• $E_T &gt; 30 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>• $</td>
<td>\eta</td>
<td>&lt; 1.4442$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ $H_T^* &gt; 400 \text{ GeV}$</td>
</tr>
</tbody>
</table>

*$H_T$ is the scalar sum of jet $p_T$ in the event
Backgrounds: QCD

- **Double photon**
  - **Dominant:** QCD with fake $\text{MET}$
    - Multijet: at least 2 jets misidentified as photons
    - $\gamma + \text{jet}$: 1 jet misidentified as a photon
    - QCD diphoton

- **Photon + lepton**
  - **Subdominant:** QCD with fake $\text{MET}$

- **Single photon**
  - **Dominant:** QCD with fake $\text{MET}$
    - $\gamma + \text{jet}$
    - QCD multijet with at least 1 jet misidentified as a photon
Estimating the QCD background (1)

- **EM << hadronic** energy resolution $\Rightarrow$ fake $\text{ME}_T$ due entirely to jet mismeasurement

- **Measure QCD background from data**—control sample with well-measured EM objects to model the QCD fake $\text{ME}_T$ spectrum

- **Reweight** $\text{ME}_T$ spectrum of control sample by $p_T^{\text{EM}}(\text{candidate})/p_T^{\text{EM}}(\text{control})$

- **Normalize** the predicted QCD fake $\text{ME}_T$ spectrum to a signal-depleted low-$\text{ME}_T$ region

### What is a well-measured EM object?

<table>
<thead>
<tr>
<th>EM objects (well measured kinematics, no fake $\text{ME}_T$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>di-EM $p_T$ (well-measured handle on the kinematics of the jet system)</td>
</tr>
<tr>
<td>2\textsuperscript{nd} most energetic EM object</td>
</tr>
<tr>
<td>Most energetic EM object</td>
</tr>
<tr>
<td>Jets (poorly measured kinematics, source of fake $\text{ME}_T$)</td>
</tr>
</tbody>
</table>

**Double photon cartoon**

**Double photon cartoon**

**Double photon cartoon**

**Double photon cartoon**

EM objects (well measured kinematics, no fake $\text{ME}_T$)

<table>
<thead>
<tr>
<th>What is a well-measured EM object?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Di-electron</strong></td>
</tr>
<tr>
<td><strong>Di-fake</strong></td>
</tr>
<tr>
<td><strong>Single fake</strong></td>
</tr>
<tr>
<td><strong>Fake lepton + fake photon</strong></td>
</tr>
</tbody>
</table>
Estimating the QCD background (2)

- **Double photon:**
  - Di-electron and di-fake control samples
  - Reweight by di-EM $p_T$
  - Normalize in $M_{ET} < 20$ GeV region

- **Single photon:**
  - Single fake control sample
  - Reweight by ratio (candidate photon $p_T$/fake $p_T$)
  - Normalize in $M_{ET} < 100$ GeV region

- **Photon + lepton:**
  - Di-electron and fake lepton + fake photon control samples
  - Reweight by di-EM $p_T$ and $p_T^l$
  - Normalize in $M_{ET} < 30$ GeV region
Backgrounds: electroweak

• Double photon
  • Subdominant: electroweak processes with real $ME_T$
    • $W(\rightarrow ev)\gamma$: electron misidentified as a photon
    • $W(\rightarrow ev)+\text{jet}$: electron and jet misidentified as photons

• Photon + lepton
  • Subdominant: jets faking photons in events with real $ME_T$
    • $W(\rightarrow ev)+\text{jet}$, $W(\rightarrow \mu\nu)+\text{jet}$
  • Subdominant: electrons faking photons
    • $Z\rightarrow ee$
    • $t\bar{t}\text{bar}$ with at least 1 $W$ decaying to an electron

• Single photon
  • Subdominant: electroweak processes with real $ME_T$
    • $W\rightarrow ev$, $Z\rightarrow ee$, or $t\bar{t}\text{bar}$ semileptonic with 1 electron misidentified as a photon
Estimating the electroweak background

- Estimate the electron→photon mis-ID rate \( f_{e\gamma} \) by fitting the di-EM invariant mass spectra in the di-electron and eγ samples.
- Scale the \( M_{T} \) distribution of an appropriate electron control sample by \( f_{e\gamma} \).
  - Double photon search: eγ sample (2 objects passing the candidate photon ID criteria; 1 with pixel match [e], 1 with pixel match veto [γ]).
  - Single photon search: single e sample (e as above) weighted by γ/e \( p_{T} \) ratio as on slide 12.
  - Photon + lepton search: lepton + e sample (e as above).
- Estimate the jet→photon mis-ID background by scaling a lepton + “fake photon” control sample by jet→photon mis-ID rate (photon + lepton search only).

\[ f_{e\gamma} = 0.014 \pm 0.002 \]
Backgrounds: MC

• Double photon
  • Negligible: irreducible backgrounds
    • $W\gamma\gamma$ (total cross section $\sim 7$ fb at 14 TeV LHC) [6]
    • $Z\gamma\gamma$

• Photon + lepton
  • Dominant: $W(\rightarrow e\nu)\gamma$, $W(\rightarrow \mu\nu)\gamma$
    • MadGraph tune D6T, BAUR NLO, K-factors range $\sim 2-3$
  • Negligible: ttbar+$\gamma$

• Single photon
  • Subdominant: initial state radiation (ISR) or final state radiation (FSR) of photons in events with no electron (e.g. ttbar/W/Z→hadrons)
    • Pythia MC with 100% uncertainty (contribution very small)
Candidate $\text{MET}_T$ spectra (1)

Double photon search

Observed events consistent with predicted background

Single photon search
Candidate $\text{MET}$ spectra (2)

Observed events consistent with predicted background

Example GGM model:
$m_{g} = m_{q} = 450$ GeV, $m_{\chi_{1}^{0}} \approx m_{\chi_{1}^{+}} = 195$ GeV
Upper limit calculation

- “Simplified model” GGM signal MC [7]
- Next to leading order production cross-sections calculated with PROSPINO 2.1
- Pythia 6.422 for hadronization and decay
- Full CMS detector simulation based on GEANT
- PDF uncertainties calculated using PDF4LHC recommendations [8]
- 3 different NLSP scenarios

1. **Bino NLSP**: $M_1 = 375$ GeV, $M_2 = 3.5$ TeV, $\tan \beta = 2$, squark and gluino masses in [400 GeV, 2000 GeV], sleptons and all gauginos except the lightest neutralino have mass 3.5 TeV, heavy right-handed squarks (GGM sum rules)

2. **Wino NLSP (1)**: $M_1 = 3.5$ TeV, $M_2 = 375$ GeV, $\tan \beta = 2$, squark and gluino masses in [400 GeV, 2000 GeV], sleptons and all gauginos except the lightest neutralino and chargino have mass 3.5 TeV, heavy right-handed squarks (GGM sum rules)

3. **Wino NLSP (2)**: $m_{\text{squark}} \sim m_{\text{gluino}}$, $\tan \beta = 2$, NLSP mass $> 100$ GeV

- CLS upper limit calculation for scenarios 1 and 2 [9], Bayesian upper limit calculation with flat prior [10] for scenario 3
Upper limits

Double photon search
Bino NLSP

CMS preliminary \( \int \frac{dL}{dt} = 1.14 \text{fb}^{-1} \) \( t \gamma, \geqslant 3 \) jets, MET > 200 GeV

Single photon search
Bino NLSP

Single photon search
Wino NLSP

Gluino mass

Squark mass
Exclusion contours for bino NLSP

Double photon search

Single photon search

<table>
<thead>
<tr>
<th>Search region</th>
<th>No. expected</th>
<th>No. observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma + \geq 1j \ + (\text{MET} &gt; 100 \text{ GeV})$</td>
<td>$1.5 \pm 0.8(\text{stat.}) \pm 0.6(\text{syst.})$</td>
<td>0</td>
</tr>
<tr>
<td>$\gamma + \geq 3j + (\text{MET} &gt; 200 \text{ GeV})$</td>
<td>$7.24 \pm 2.6(\text{stat.}) \pm 1.53(\text{syst.})$</td>
<td>7</td>
</tr>
</tbody>
</table>
Bino NLSP exclusion in the $m_{\text{gluino}}-m_{\text{neutralino}}$ plane

- Double photon search
- $m_{\text{squark}} = 2.5$ TeV
- Exact same analysis, exclusion just plotted in a different plane

CMS Preliminary, $\sqrt{s} = 7$ TeV, $\int L dt = 1.14$ fb$^{-1}$

- $m_q = 2500$ (GeV/c$^2$)
- Observed, NLO
- Expected, NLO
- $\pm 1\sigma$, NLO

Excluded $\tilde{g}$ NLSP

Brand new for SUSY11!
Exclusion contours for wino NLSP

**Single photon search**

\( \gamma, \geq 3 \text{ jets}, \text{MET} > 200 \text{ GeV} \)

**Photon + lepton search**

<table>
<thead>
<tr>
<th>Search region</th>
<th>No. expected</th>
<th>No. observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma + e + (\text{MET} &gt; 100 \text{ GeV}) )</td>
<td>( 1.74 \pm 0.43(\text{stat.} \oplus \text{syst.}) )</td>
<td>1</td>
</tr>
<tr>
<td>( \gamma + \mu + (\text{MET} &gt; 100 \text{ GeV}) )</td>
<td>( 1.59 \pm 0.39(\text{stat.} \oplus \text{syst.}) )</td>
<td>1</td>
</tr>
<tr>
<td>( \gamma + \geq 3j + (\text{MET} &gt; 200 \text{ GeV}) )</td>
<td>( 7.24 \pm 2.6(\text{stat.}) \pm 1.53(\text{syst.}) )</td>
<td>7</td>
</tr>
</tbody>
</table>
Conclusions

- Searches in double photon, single photon, and photon + lepton final states are powerful tools for observing SUSY
- Clean trigger objects
- Manageable backgrounds that can mostly be estimated from data
- CMS actively searching for gauge-mediated SUSY in a variety of ways
  - In the classic bino NLSP scenario, $m_{\text{squark}} = m_{\text{gluino}} \sim 950$ GeV excluded
  - In the wino NLSP scenario, $m_{\text{gluino}} \sim 650$ GeV excluded, independently of $m_{\text{squark}}$ and $m_{\text{wino}}$

CMS simulation

$m_{\text{squark}} = 1.25$ TeV, $m_{\text{gluino}} = 1.2$ TeV, $m_{\text{neutralino}} = 225$ GeV
Backup
General gauge mediation at the LHC

- General gauge mediation (GGM)
  - Definition of gauge mediation: the MSSM and the SUSY-breaking sector are linked only by nonzero values of the MSSM gauge coupling constants
  - Different theories of gauge mediation can arise from the single general framework
  - Prescription provided for calculating the soft masses of the spectrum
  - SUSY-breaking sector leads to mass relations between the sfermions, constraining the allowed parameter space

- Consequences for phenomenology
  1. Enhancement of gg parton luminosity at the LHC with respect to quark-antiquark ⇒ can quickly probe models with light colored particles
  2. Lightest neutralino NLSP can be bino, wino, or higgsino, leading to distinct and exotic LHC final states
Photons

- Isolated from jets
  - Tracker and calorimeter isolation + electromagnetic calorimeter (ECAL) shower shape variables reject photons within jets (i.e. from π⁰ decay)
  - Ratio of energy in the hadronic calorimeter (HCAL) directly behind the photon candidate to ECAL energy rejects jets that have begun to shower in the ECAL
- Inconsistent with ECAL noise
- No matching hit in the silicon pixel detector
Photons
- Isolated from jets
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- Ratio of energy in the hadronic calorimeter (HCAL) directly behind the photon candidate to ECAL energy rejects jets that have begun to shower in the ECAL
- Inconsistent with ECAL noise
- No matching hit in the silicon pixel detector

Jets and $\mathbf{M}_{\mathbf{E}}$
- Particle-flow (PF) jets (anti-$k_T$ algorithm with $R = 0.5$)
- Inconsistent with HCAL noise
- Corrected for pileup, $p_T$ response, and $\eta$ response
- PF $\mathbf{M}_{\mathbf{E}}$ built from PF tracks and calorimeter clusters with jet corrections applied
Jets and $\text{MET}$

**Why jets?**
- Strong production of SUSY guarantees at least 1 hard jet per event
- Jet requirement helps to suppress dijet and $\gamma$+jet backgrounds

**Photons**
- Isolated from jets
  - Tracker and calorimeter isolation + electromagnetic calorimeter (ECAL) shower shape variables reject photons within jets (i.e. from $\pi^0$ decay)
  - Ratio of energy in the hadronic calorimeter (HCAL) directly behind the photon candidate to ECAL energy rejects jets that have begun to shower in the ECAL
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**Jets and $\text{MET}$**
- Particle-flow (PF) jets (anti-$k_T$ algorithm with $R = 0.5$)
- Inconsistent with HCAL noise
- Corrected for pileup, $p_T$ response, and $\eta$ response
- PF $\text{MET}$ built from PF tracks and calorimeter clusters with jet corrections applied

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[5]
Electrons and muons

- **Leptons**
  - **Electrons**
    - Isolated from jets (similar to photon isolation)
    - Inconsistent with ECAL noise
    - Good quality track match to ECAL cluster
    - Inconsistent with photon conversion
    - Within barrel muon trigger acceptance
  - **Muons:**
    - Isolated from jets (similar to photon isolation)
    - Good quality track
    - Matched to trigger object
    - Within barrel muon trigger acceptance

- **Photons**
  - Isolated from jets
    - Tracker and calorimeter isolation + electromagnetic calorimeter (ECAL) shower shape variables reject photons within jets (i.e. from π⁰ decay)
    - Ratio of energy in the hadronic calorimeter (HCAL) directly behind the photon candidate to ECAL energy rejects jets that have begun to shower in the ECAL
    - Inconsistent with ECAL noise
    - No matching hit in the silicon pixel detector

- **Jets and ME_T**
  - Particle-flow (PF) jets (anti-k_T algorithm with R = 0.5)
  - Inconsistent with HCAL noise
  - Corrected for pileup, p_T response, and η response
  - PF ME_T built from PF tracks and calorimeter clusters with jet corrections applied
### Photon isolation criteria

- **ECAL isolation energy** $< 0.006 E_T + 4.2$ GeV
- **HCAL isolation energy** $< 0.0025 E_T + 2.2$ GeV
- **Tracker isolation energy** $< 0.001 E_T + 2.0$ GeV

**HCAL energy in R < 0.15 cone around photon candidate**

$$\frac{\text{ECAL energy of photon candidate}}{\text{HCAL energy in R < 0.15 cone around photon candidate}} < 0.05$$

$$\sigma_{\eta\eta}^2 = \frac{\sum_{i=1}^{25} w_i (\eta_i - \bar{\eta})^2}{\sum_{i=1}^{25} w_i} < 0.011$$

where $w_i = \max(0, 4.7 + \ln(E_i/E))$, $E_i$ is the energy of the $i^{th}$ crystal in a group of $5 \times 5$ centred on the one with the highest energy, and $\eta_i = \hat{\eta}_i \times \delta\eta$, where $\hat{\eta}_i$ is the $\eta$ index of the $i^{th}$ crystal and $\delta\eta = 0.0174$; $E$ is the total energy of the group and $\bar{\eta}$ the average $\eta$ weighted by $w_i$ in the same group [12].
ECAL noise cleaning

1. Form $3 \times 3$ matrix of crystals around the photon seed crystal
2. Find the 2 highest energy crystals within the matrix
3. If the sum of the energies of the 2 highest energy crystals divided by the sum of the energies of all 9 crystals within the matrix exceeds 0.95, reject the photon as ECAL noise

\[
\frac{E_{\text{red}} + E_{\text{blue}}}{E_{3\times3}} > 0.95 \Rightarrow \text{reject}
\]
Photon ID variables

**ECAL**

- MC $\gamma$ partonic
- MC $\gamma$ ISR/FSR
- MC other

**HCAL**

- Data
- MC $\gamma$ partonic
- MC $\gamma$ ISR/FSR
- MC other

**Track**

- Data
- MC $\gamma$ partonic
- MC $\gamma$ ISR/FSR
- MC other

**Summary**

- CMS Preliminary 2010
- $\sqrt{s} = 7$ TeV
- $L = 74$ nb$^{-1}$
- $|\eta| < 1.4442$

- Photon ID variables distributions are shown before cutting on the variables for photon identification. The Monte Carlo results are normalized separately for each plot to the number of entries in the data histogram.

- Photon isolation and isolation distributions for data and MC, shown for barrel (right) and endcap (left).
Photon/lepton ID efficiency

- Photon and lepton ID efficiencies taken from MC and corrected by \((\text{data efficiency})/(\text{MC efficiency})\)
  - \(Z \rightarrow \mu\mu\) events for muons
  - \(Z \rightarrow \text{ee}\) events for electrons and photons
    - Photon ID cuts designed to behave similarly for electrons and photons
- Signal MC acceptance \(\times\) efficiency multiplied by 1 factor of \(\varepsilon_{\text{data}}/\varepsilon_{\text{MC}}\) per photon or lepton
- Pixel match veto efficiency estimated from MC: \((96.4 \pm 0.5)\)% (stat. \(\oplus\) syst. due to tracker material budget variation)

<table>
<thead>
<tr>
<th>Particle</th>
<th>(\varepsilon_{\text{data}}/\varepsilon_{\text{MC}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon</td>
<td>0.945 (\pm) 0.068</td>
</tr>
<tr>
<td>Electron</td>
<td>0.928 (\pm) 0.015</td>
</tr>
<tr>
<td>Muon</td>
<td>0.990 (\pm) 0.001</td>
</tr>
</tbody>
</table>

Errors on photon efficiency scale factor:
- Stat. \(\oplus\)
- Syst.(Z signal and background shape variation) \(\oplus\)
- Syst.(signal fit over/underestimation) \(\oplus\)
- Syst.(pileup effects) \(\oplus\)
- Syst.(MC electron/photon difference)
HCAL noise cleaning

1. $f_{\text{HPD}} \leq 0.98$, where $f_{\text{HPD}}$ is the fraction of the jet’s energy contributed by the highest energy hybrid photodetector

2. $n_{90\text{Hits}} > 1$, where $n_{90\text{Hits}}$ is the minimum number of HCAL channels containing 90% of the jet’s energy

3. $\text{EMF} \geq 0.01$, where EMF is the electromagnetic fraction of the jet’s energy

See [14]
Particle flow (PF) algorithm (1)

- Main idea: reconstruct each individual stable particle traversing the detector using an optimal combination of tracking and calorimetric information, with the aim of achieving the best possible energy resolution

1. Reconstruct the fundamental detector objects via iterative procedures
   - Tracks in the inner silicon layers
     - High efficiency and low fake rate for charged hadrons in jets
     - Relaxed primary vertex constraint allows photon conversions, particles originating from nuclear interactions in the silicon, and long-lived particles to be reconstructed
   - Calorimeter clusters
   - Muon tracks in the outer muon layers

2. Create a “block” of linked fundamental objects
   - Link silicon tracks to calorimeter clusters via $\Delta R_{\text{track-cluster}}$ (account for electron bremsstrahlung)
   - Link clusters in one calorimeter layer to clusters in a separate layer via $\Delta R_{\text{cluster-cluster}}$
   - Link silicon tracks to muon tracks via global track $X^2$
Particle flow (PF) algorithm (2)

3. ID the particles in the block
   • If global (silicon + muon layers) muon $p_T$ is compatible with silicon track $p_T$, ID as a muon and remove corresponding tracks from block
   • ID electron tracks via special algorithm and removed all corresponding tracks and cluster from block
   • Remove fake tracks from the block
   • Remove excess track-cluster links via $\Delta R_{\text{track-cluster}}$ minimization (but allow multiple tracks to be associated to one cluster)
   • If the cluster energy is significantly larger then the energy of the linked track, ID as a PF photon or PF neutral hadron and remove corresponding clusters from the block
   • If the cluster is not linked to a track, ID as a PF photon or PF neutral hadron and remove corresponding clusters from the block
   • Remaining track-cluster links are PF charged hadrons

• Better performance in terms of jet energy resolution and jet energy correction uncertainties than typical calorimeter-only jet algorithms
• See [15] for details and performance in LHC data
## Electron selection

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB</td>
<td>EE</td>
<td>EB = ECAL barrel, EE = ECAL endcap</td>
</tr>
<tr>
<td>$p_T$</td>
<td>$&gt;20$ GeV</td>
<td>$&gt;20$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>ECAL isolation</td>
<td>$&lt;0.07 E_T$</td>
<td>$&lt;0.05 E_T$</td>
</tr>
<tr>
<td>HCAL isolation</td>
<td>$&lt;0.01 E_T$</td>
<td>$&lt;0.025 E_T$</td>
</tr>
<tr>
<td>Track isolation</td>
<td>$&lt;0.09 E_T$</td>
<td>$&lt;0.04 E_T$</td>
</tr>
<tr>
<td>Missing track hits</td>
<td>$\leq 0$</td>
<td>$\leq 0$</td>
</tr>
<tr>
<td>$\Delta(cot \theta)$</td>
<td>$&lt;0.02$</td>
<td>$&lt;0.02$</td>
</tr>
<tr>
<td>Dist</td>
<td>$&lt;0.02$</td>
<td>$&lt;0.02$</td>
</tr>
<tr>
<td>$\sigma_{\eta\eta}$</td>
<td>$&lt;0.01$</td>
<td>$&lt;0.03$</td>
</tr>
<tr>
<td>$\Delta \phi_{in}$</td>
<td>$&lt;0.06$</td>
<td>$&lt;0.03$</td>
</tr>
<tr>
<td>$\Delta \eta_{in}$</td>
<td>$&lt;0.004$</td>
<td>$&lt;0.007$</td>
</tr>
<tr>
<td>H/E</td>
<td>$&lt;0.04$</td>
<td>$&lt;0.025$</td>
</tr>
</tbody>
</table>
## Muon selection

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>$&gt;20$ GeV</td>
<td>Geometrical acceptance of the muon high level trigger</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;$</td>
</tr>
<tr>
<td>Combined isolation</td>
<td>$&lt;0.15$</td>
<td>Tracker muon = reconstructed from tracker hits only; global muon = reconstructed from tracker and muon station hits</td>
</tr>
<tr>
<td>Reconstruction algorithm</td>
<td>Global and tracker</td>
<td></td>
</tr>
<tr>
<td>Muon chamber hits</td>
<td>$\geq 1$</td>
<td></td>
</tr>
<tr>
<td>Tracker muon match</td>
<td>$\geq 2$ muon chambers</td>
<td></td>
</tr>
<tr>
<td>Tracker hits</td>
<td>$&gt;10$</td>
<td></td>
</tr>
<tr>
<td>Pixel hits</td>
<td>$\geq 1$</td>
<td></td>
</tr>
<tr>
<td>$\chi^2/\text{ndof}$</td>
<td>$&lt;10$</td>
<td>Global muon track fit</td>
</tr>
<tr>
<td>$</td>
<td>d_{xy}</td>
<td>$</td>
</tr>
<tr>
<td>High level trigger match</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
Backgrounds

• **Double photon**
  - Dominant: QCD with fake ME$_T$
    - Multijet: at least 2 jets misidentified as photons
    - γ + jet: 1 jet misidentified as a photon
    - QCD diphoton
  - Subdominant: electroweak processes with real ME$_T$
    - $W(\rightarrow ev)\gamma$: electron misidentified as a photon
    - $W(\rightarrow ev)+jet$: electron and jet misidentified as photons
  - Negligible: irreducible backgrounds
    - $W\gamma\gamma$ (total cross section $\sim 7$ fb at 14 TeV LHC) [6]
    - $Z\gamma\gamma$

• **Photon + lepton**
  - Dominant: $W(\rightarrow ev)\gamma$, $W(\rightarrow \mu\nu)\gamma$
  - Subdominant: jets faking photons in events with real ME$_T$
    - $W(\rightarrow ev)+jet$, $W(\rightarrow \mu\nu)+jet$
  - Subdominant: electrons faking photons
    - $Z\rightarrow ee$
    - ttbar with at least 1 $W$ decaying to an electron
  - Subdominant: QCD with fake ME$_T$
  - Negligible: ttbar+$\gamma$

• **Single photon**
  - Dominant: QCD with fake ME$_T$
    - γ+jet
    - QCD multijet with at least 1 jet misidentified as a photon
  - Subdominant: electroweak processes with real ME$_T$
    - $W\rightarrow ev$, $Z\rightarrow ee$, or ttbar semileptonic with 1 electron misidentified as a photon
    - Initial state radiation (ISR) or final state radiation (FSR) of photons in events with no electron
### Fake electron

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>$&gt;20$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>ECAL isolation</td>
<td>$&lt;0.07E_T$</td>
</tr>
<tr>
<td>HCAL isolation</td>
<td>$&lt;0.01E_T$</td>
</tr>
<tr>
<td>Track isolation</td>
<td>$&lt;0.09E_T$</td>
</tr>
<tr>
<td>Missing track hits</td>
<td>$\leq 0$</td>
</tr>
<tr>
<td>$\Delta:\cot \theta$</td>
<td>$&lt;0.02$</td>
</tr>
<tr>
<td>Dist</td>
<td>$&lt;0.02$</td>
</tr>
<tr>
<td>$\Delta\eta_{in}$</td>
<td>$&lt;0.06$</td>
</tr>
<tr>
<td>$\Delta\eta_{in}$</td>
<td>$&lt;0.004$</td>
</tr>
</tbody>
</table>

### Fake muon

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>$&gt;20$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Combined isolation</td>
<td>0.15-0.25</td>
</tr>
<tr>
<td>Reconstruction algorithm</td>
<td>Global and tracker</td>
</tr>
<tr>
<td>Muon chamber hits</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>Tracker muon match</td>
<td>$\geq 2$ muon chambers</td>
</tr>
<tr>
<td>Tracker hits</td>
<td>$&gt;10$</td>
</tr>
<tr>
<td>Pixel hits</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>$\chi^2/ndof$</td>
<td>$&lt;10$</td>
</tr>
<tr>
<td>$</td>
<td>d_{xy}</td>
</tr>
<tr>
<td>High level trigger match</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### EM object

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>$&gt;30$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>ECAL isolation</td>
<td>$&lt;0.006E_T + 4.2$ GeV</td>
</tr>
<tr>
<td>HCAL isolation</td>
<td>$&lt;0.0025E_T + 2.2$ GeV</td>
</tr>
<tr>
<td>Track isolation</td>
<td>$&lt;10$ GeV</td>
</tr>
<tr>
<td>H/E</td>
<td>$&lt;0.05$</td>
</tr>
<tr>
<td>Noise-cleaned</td>
<td>Yes</td>
</tr>
<tr>
<td>Pixel match</td>
<td>No</td>
</tr>
</tbody>
</table>

**Fake electron:** electron with only isolation requirements

**Fake muon:** muon with relaxed isolation requirement

**EM object:** photon with relaxed track isolation and no shower shape requirement
Event selection

- Using the CMS reconstructed physics objects, build 3 different event selections corresponding to the 3 GGM topologies

<table>
<thead>
<tr>
<th>Topology</th>
<th>No. isolated photons</th>
<th>No. isolated leptons (e or (\mu))</th>
<th>No. jets</th>
<th>Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double photon</td>
<td>(\geq 2) with:</td>
<td></td>
<td>(\geq 1) with:</td>
<td>Single-leg seeded double photon trigger:</td>
</tr>
<tr>
<td></td>
<td>• Leading (E_T &gt; 45) GeV</td>
<td></td>
<td>• (E_T &gt; 30) GeV</td>
<td>• Leading/trailing (E_T &gt; 32/26, 36/22, ) or 40/28 GeV</td>
</tr>
<tr>
<td></td>
<td>• Trailing (E_T &gt; 30) GeV</td>
<td></td>
<td>• (</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>• (</td>
<td>\eta</td>
<td>&lt; 1.4442)</td>
<td></td>
</tr>
<tr>
<td>Photon + lepton</td>
<td>(\geq 1) with:</td>
<td>(\geq 1) with:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• (E_T &gt; 30) GeV</td>
<td>• (E_T &gt; 20) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• (</td>
<td>\eta</td>
<td>&lt; 1.4442)</td>
<td>• (</td>
</tr>
<tr>
<td>Single photon</td>
<td>(\geq 1) with:</td>
<td></td>
<td>(\geq 3) with:</td>
<td>Single-photon + (H_T) trigger:</td>
</tr>
<tr>
<td></td>
<td>• (E_T &gt; 75) GeV</td>
<td></td>
<td>• (E_T &gt; 30) GeV</td>
<td>• Photon (E_T &gt; 70) GeV</td>
</tr>
<tr>
<td></td>
<td>• (</td>
<td>\eta</td>
<td>&lt; 1.4442)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(+ H_T^* &gt; 400) GeV</td>
<td></td>
</tr>
</tbody>
</table>

\(H_T^*\) is the scalar sum of jet \(p_T\) in the event
Single fake definition

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>$&gt;70 \text{ GeV}$</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>ECAL isolation</td>
<td>$&lt;\min(10 \times (0.006E_T + 4.2 \text{ GeV}), 0.3E_T)$</td>
</tr>
<tr>
<td>HCAL isolation</td>
<td>$&lt;\min(10 \times (0.0025E_T + 2.2 \text{ GeV}), 0.3E_T)$</td>
</tr>
<tr>
<td>Track isolation</td>
<td>$&lt;\min(10 \times (0.001E_T + 3.5 \text{ GeV}), 0.3E_T)$</td>
</tr>
<tr>
<td>Pixel seed</td>
<td>No</td>
</tr>
<tr>
<td>R9</td>
<td>$&lt;0.98$</td>
</tr>
<tr>
<td>Trigger</td>
<td>Yes</td>
</tr>
</tbody>
</table>

and

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAL isolation</td>
<td>$(0.006E_T + 4.2 \text{ GeV})$</td>
</tr>
<tr>
<td>and</td>
<td></td>
</tr>
<tr>
<td>HCAL isolation</td>
<td>$(0.0025E_T + 2.2 \text{ GeV})$</td>
</tr>
<tr>
<td>or</td>
<td></td>
</tr>
<tr>
<td>Track isolation</td>
<td>$(0.001E_T + 3.5 \text{ GeV})$</td>
</tr>
<tr>
<td>or</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\eta\eta}$</td>
<td>$&gt;0.011$</td>
</tr>
<tr>
<td>or</td>
<td></td>
</tr>
<tr>
<td>$H/E$</td>
<td>$&gt;0.05$</td>
</tr>
</tbody>
</table>
The number of events in the di-electron sample is given by

\[ N_{ee} = f_{e \to e}^2 N_{Z \to ee} \]

where \( f_{e \to e} \) is the efficiency to correctly identify an electron via pixel match and \( N_{Z \to ee} \) is the true number of \( Z \to ee \) events. The number of events in the e\( \gamma \) sample due to misidentification of 1 Z electron as a photon is given by

\[ N_{Ze\gamma} = 2 f_{e \to e} (1 - f_{e \to e}) N_{Z \to ee} \]

Solving for \( f_{e \to e} \),

\[ f_{e \to e} = \frac{1}{1 + \frac{1}{2} \frac{N_{Z}^{Z}}{N_{ee}}} \]

The number of events in the e\( \gamma \) sample due to correctly identifying a W electron is given by

\[ N_{e\gamma}^{W} = f_{e \to e} N_{W} \]

where \( N_{W} \) is the number of true \( W \to e\nu \) events. The number of \( \gamma \gamma \) events from W electron misidentification is given by

\[ N_{\gamma\gamma}^{EW} = (1 - f_{e \to e}) N_{W} \]

where we have neglected the contribution from Z electron misidentification since it is small (i.e., \( f_{e \to \gamma} \) is small and the Z contribution involves \( f_{e \to \gamma}^2 \), since both electrons have to be misidentified). Since

\[ f_{e \to e} = 1 - f_{e \to \gamma} \]

solving for \( N_{\gamma\gamma}^{EW} \)

\[ N_{\gamma\gamma}^{EW} = \frac{f_{e \to \gamma}}{1 - f_{e \to \gamma}} N_{e \to \gamma} \]
Check of the background estimation

• Question: Can the QCD background prediction method described on slide 11 correctly predict the QCD contribution to the \(e\gamma\) (W-like) sample?

• Answer: Yes

• Reweight the di-electron \(\mathcal{E}_T\) spectrum such that the di-electron \(p_T\) spectrum matches the \(e\gamma\) di-EM \(p_T\) spectrum (i.e. use the method described on slide 11 to get a prediction for the QCD component of the \(e\gamma\) sample)

• Observe an excess (esp. for \(\mathcal{E}_T > 30\) GeV) of \(e\gamma\) events over the predicted QCD background

• Excess is consistent with expected yield of \(W\gamma\) and \(W+\)jet Monte Carlo (MC)
Estimating the jet→γ backgrounds

- Jet→γ fake rate determination
  - Muon-, jet-, and photon-triggered datasets to determine the fake rate
  - Fake rate = (# of photons)/(# of fakeable objects)
    - Fakeable object: still EM-like, but failing some important photon ID cuts
  - Real photon component in tight photon sample extracted from fit to MC shower shape template and subtracted
  - Strong dependence on $p_T$, no dependence on $|\eta|$ in EB
  - $\text{MET}$ spectrum of lepton + fakeable object data control sample weighted by $E_T$-dependent fake rate

Fakeable object definition:

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>$&gt;20$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>ECAL isolation</td>
<td>$&lt;\min(5 \times (0.006E_T + 4.2 \text{ GeV}), 0.2E_T)$</td>
</tr>
<tr>
<td>HCAL isolation</td>
<td>$&lt;\min(5 \times (0.0025E_T + 2.2 \text{ GeV}), 0.2E_T)$</td>
</tr>
<tr>
<td>Track isolation</td>
<td>$&lt;\min(5 \times (0.001E_T + 3.5 \text{ GeV}), 0.2E_T)$</td>
</tr>
</tbody>
</table>

and

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAL isolation</td>
<td>$&gt;(0.006E_T + 4.2 \text{ GeV})$</td>
</tr>
<tr>
<td>or</td>
<td></td>
</tr>
<tr>
<td>HCAL isolation</td>
<td>$&gt;(0.0025E_T + 2.2 \text{ GeV})$</td>
</tr>
<tr>
<td>or</td>
<td></td>
</tr>
<tr>
<td>Track isolation</td>
<td>$&gt;(0.001E_T + 3.5 \text{ GeV})$</td>
</tr>
<tr>
<td>or</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\eta\eta}$</td>
<td>$&gt;0.013$</td>
</tr>
</tbody>
</table>

Cut Value

- $E_T$
Estimating backgrounds from MC

- **Wγ background in photon + lepton search**
  - Modeled with MadGraph MC, tune D6T
  - K-factors estimated from BAUR NLO generator using CTEQ66 NLO PDF sets
  - K-factors range from ~2-3, depending on photon $E_T$
  - Leading order photon $E_T$ spectrum modified by K-factors, but $M_E$ and $M_T$ distributions are much more stable with respect to NLO effects

- Background to single photon search from $t\bar{t}$/$W$/$Z \rightarrow$ hadrons + ISR/FSR photon is small (total <1 event in $M_E \geq 200$ GeV vs. ~10 events from other background sources) and taken from Pythia MC simulation with 100% uncertainty

Syst.(10% from halving/doubling factorization and renormalization scale) ⊕ syst.(<2% PDF uncertainty [16]) ⊕ syst.(4% luminosity)
Table of backgrounds

<table>
<thead>
<tr>
<th>Type</th>
<th>Events</th>
<th>stat. error</th>
<th>scal. error</th>
<th>norm. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$ candidates</td>
<td>0</td>
<td>±2.19</td>
<td>±0.13</td>
<td>±0.10</td>
</tr>
<tr>
<td>$ff$ QCD background</td>
<td>2.3 ± 2.2</td>
<td>±0.82</td>
<td>±0.02</td>
<td>±0.03</td>
</tr>
<tr>
<td>$ee$ QCD background</td>
<td>0.8 ± 0.8</td>
<td>±0.06</td>
<td>±0.00</td>
<td>±0.03</td>
</tr>
<tr>
<td>EWK background</td>
<td>0.3 ± 0.1</td>
<td>±2.19</td>
<td>±0.13</td>
<td>±0.10</td>
</tr>
<tr>
<td>Total background ($ff$)</td>
<td>2.5 ± 2.2</td>
<td>±2.19</td>
<td>±0.13</td>
<td>±0.10</td>
</tr>
<tr>
<td>Total background ($ee$)</td>
<td>1.3 ± 0.8</td>
<td>±2.19</td>
<td>±0.13</td>
<td>±0.10</td>
</tr>
</tbody>
</table>

Errors: stat. $\oplus$ syst. (ME$_T$ shape from reweighting) $\oplus$ syst. (normalization)

Double photon

Single photon

Photon + lepton
NLO cross sections

CMS preliminary $\int L dt = 1.14 fb^{-1} \quad 1\gamma, \geq 3 \text{ jets, MET}> 200 \text{ GeV}$

Bino NLSP

Wino NLSP
\( \text{MET with(out) jet requirement} \)

**No jet requirement**

**1+ jet requirement**
Simulated GGM single photon event display
References

7. http://lhcnnewphysics.org/p.000.00.r000