BSM searches with photons

Workshop on Photon Physics at the LHC
LPNHE
19/05/2015

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Overview

• **Photon-based BSM analyses (based on the 8 TeV run-1 data):**
  - $\gamma + X$ resonance searches
  - $\gamma + X$ searches
  - BSM through $H \rightarrow \gamma X$
  - Non-pointing $\gamma$

• **Using the photon as a tool in other BSM searches: an example**

• **Summary and perspectives**
$\gamma+X$ resonance searches
• Based on the SM-like Higgs boson search
• At least two photons with $E_T/m_{\gamma\gamma} > 1/3$ (1/4)
• Increase sensitivity by subdividing the events into classes (different mass resolution and predicted S/B):
  – Minimum R9 (Sum E of 3x3 crystals centered on the most energetic one divided by the energy of the supercluster)
  – Maximum $\eta$ of the photons
• Describe BG using a functional form (can't go to higher masses as too few events)
$\gamma\gamma$ resonance in ATLAS in the 65 - 600 GeV mass range

- $\geq 2$ tight photons with $E_T > 22$ GeV
- Two analyses:
  
  **Low mass: 65-110 GeV**
  
  - 3 categories (converted / unconverted combinations)
  
  - $Z$ peak: $Z(\mu\mu) + e\rightarrow\gamma$ corrections, normalized with $e\rightarrow\gamma$ rate ($e\gamma/ee$ in $Z(\mu\mu)$ peak)

  - Fit of the continuum with a functional form

  **High-mass analysis: 110-600 GeV**

  - $E_{T,1(2)}/m_{\gamma\gamma} > 0.4$ (0.3)

  - Higgs peak: double-sided Crystal Ball ($m=125.9$ GeV) + SM cross section

  - Fit of the continuum with a functional form
\( \gamma\gamma \) resonance in ATLAS in the 65 - 600 GeV mass range

Phys. Rev. Lett. 113, 171801

\[ \sqrt{s} = 8 \text{ TeV}, \int L dt = 20.3 \text{ fb}^{-1} \]

\[
\sigma_{\text{fid}} BR(X \to \gamma\gamma) = \frac{N_{\text{data}}}{C_X \mathcal{L}} \quad \text{with} \quad C_X = \frac{N_{\text{reco}}^{\text{MC}}}{N_{\text{fid}}^{\text{MC}}} \]

ATLAS
At least two tight photons with $E_T > 50$ GeV

Use the two leading photons

Isolated photons:
- The expected contribution from photon leakage outside the central core is subtracted, but fluctuations around the expected leakage grows with $E_T$
- Significant inefficiencies if using a fixed cut on the isolation:
- Vary the isolation requirement with $E_T$, from <8 GeV to <13 GeV at 1 TeV
High-mass $\gamma\gamma$ resonance in ATLAS

- Main BG: SM diphoton, Pythia (LO) + DIPHOX (NLO + fragmentation)
- Normalized to data in the low-mass region

In lower-mass analyses, it is more accurate to rely on sidebands, but this can't be done here, as insufficient event yields...

Diphoton mass spectrum

ATLAS

Control region

\[
\int L \ dt = 20.3 \text{ fb}^{-1} \\
\sqrt{s} = 8 \text{ TeV}
\]

- Data
- Total background
- Reducible background
- $\text{syst} \oplus \text{stat (reducible)}$
- $\text{syst} \oplus \text{stat (total)}$
- RS, $1/\sqrt{N_f} = 0.1, m_{\gamma\gamma} = 1.5 \text{ TeV}$
- RS, $1/\sqrt{N_f} = 0.1, m_{\gamma\gamma} = 2.0 \text{ TeV}$

Significance

$200 \ 300 \ 400 \ 500 \ 1000 \ 2000 \ 3000$

$m_{\gamma\gamma} [\text{GeV}]$
High-mass $\gamma\gamma$ resonance in ATLAS

- Main BG: SM diphoton, Pythia (LO) + DIPHOX (NLO + fragmentation)
- Normalized to data in the low-mass region
- Need to know the reducible (gamma+jet, dijet) BG component in this region:
  - Template fit to the isolation energy distribution
  - Fake template: loose but not tight photons
  - True template: tight - fake contribution normalized in the $E_{T}^{\text{iso}}>10$ GeV region

\[ \text{arxiv:1504.05511 submitted to PRD} \]
High-mass $\gamma \gamma$ resonance in ATLAS

arxiv:1504.05511 submitted to PRD

- **Interpretation:**
  - Randall-Sundrum (RS) model of extra dimension
  - Can address the hierarchy problem as gravity can propagate in extra dimension, diluting it

Limits on the lightest Kaluza-Klein graviton for different coupling strengths:

$$\int L \, dt = 20.3 \, \text{fb}^{-1}$$
One advantage of the $\gamma$ + jet search is that it can be sensitive in a lower mass region with respect to dijet searches (higher hadronic trigger thresholds).

**ATLAS**

- $\geq 1$ photon $E_T > 125$ GeV, $|\eta| < 1.37$
- $E_T^{\text{iso}}(0.4) < 0.011 E_T^{\gamma} + 3.65$ GeV
- $\geq 1$ AKt6 jet, $|\eta| < 2.8$, $p_T > 125$ GeV, $\Delta R(\gamma,j) > 1.0$
- $\Delta\eta(\gamma,j) < 1.6$
- Functional form for background

**CMS**

- $\geq 1$ photon $E_T > 170$ GeV, $|\eta| < 1.37$
- $E_T$-dependent iso $\Delta R=0.3$ ($\gamma$, charged/neutral hadrons)
- $\geq 1$ AKt5 jet, $|\eta| < 3.0$, $p_T > 170$ GeV, $\Delta R(\gamma,j) > 0.5$
- $\Delta\eta(\gamma,j) < 2.0$, $\Delta\phi(\gamma,j) > 1.5$, $m_{\gamma j} > 560$ GeV
- Functional form for background

---

**Graphs**

**ATLAS**

$f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1(1-x)^{p_2} x^{-(p_3 + p_4 \ln x)}$

**CMS**

$\frac{d\sigma}{dm} = \frac{P_0 (1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln (m/\sqrt{s})}}$
Non-thermal quantum black hole (QBH):

- Extra dimensions model lowers the Planck mass to $M_D$: possibility to create QBH.
- The ones produced near $M_D$ would evaporate faster than they thermalize: decay into a few particles rather than high-multiplicity final states.

**Excited quarks**

*(same limit in ATLAS)*
- At least one tight photon $E_T > 40$ GeV, $E_T^{\text{iso}}(0.4) < 4$ GeV
- Isolated electrons and muons $p_T > 25$ GeV, $\Delta R(l,\gamma) > 0.7$
- W SR: 1 lepton, MET $> 35$ GeV, $m_{e\gamma} \neq Z$ mass ($\pm 15$ GeV)
- Z SR: 2 leptons SFOS $m_\perp$ in 65-115 GeV
- Functional form for BG (sum of two exponentials) between 180 and 1600 GeV
Limits on narrow technimeson resonances in a model of low scale technicolour.
Photon + X searches
Photon + MET

Selection:
- $\geq 1$ photon $E_T > 125$ GeV, $|\eta| < 1.37$, $E_T^{\text{iso}}(0.4) < 5$ GeV
- MET $> 150$ GeV, $\Delta\phi(MET,\gamma) > 0.4$
- $\leq 1$ jet $p_T > 30$ GeV, $\Delta\phi(j,MET) > 0.4$
- Veto $e(\mu) p_T > 7(6)$ GeV

Background estimation:
- $Z(\nu\nu)\gamma$ and $W(\ell\nu)\gamma$ normalized using a fit to data in multiple CR ($Z(ee)\gamma$, $Z(\mu\mu)\gamma$, $W(\nu\nu)\gamma$)
- Jet fake using isolation / ID
- Electron fake using tag & probe method on $Z(ee)$ applied on a $W(e\nu)$ CR

Cut and count

---

Selection:
- $\geq 1$ photon $E_T > 145$ GeV, $|\eta| < 1.44$, $E_T$-dependent iso $\Delta R = 0.3$ ($\gamma$,charged/neutral hadrons)
- MET $> 140$ GeV, $\Delta\phi(MET,\gamma) > 2.0$
- $\leq 1$ jet $p_T > 30$ GeV
- Veto $e,\mu p_T > 10$ GeV

Background estimation:
- $Z(\nu\nu)\gamma$, $W(\ell\nu)\gamma$ from MC (cross checked in $Z(\ell\ell)\gamma$)
- Jet fake using isolation / ID (shower width)
- Electron fake using tag & probe method on $Z(ee)$ applied on a $W(e\nu)$ CR
- Non-collision BG: reverting the beam halo tag (evidence in ECAL of a MIP roughly parallel to the beam axis)

Limits using a shape fit to $E_T^{\gamma}$
Photon + MET


### ATLAS

**Zll CR**

\[
\int L \, dt = 20.3 \, \text{fb}^{-1} \, \sqrt{s} = 8 \, \text{TeV}
\]

Data/Bkg. uncertainty

<table>
<thead>
<tr>
<th>Process</th>
<th>Event yield (SR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z(\to \nu \nu) + \gamma)</td>
<td>(389 \pm 36 \pm 10)</td>
</tr>
<tr>
<td>(W(\to \ell \nu) + \gamma)</td>
<td>(82.5 \pm 5.3 \pm 3.4)</td>
</tr>
<tr>
<td>(W/Z + \text{jet, } t\bar{t}, \text{diboson})</td>
<td>(83 \pm 2 \pm 28)</td>
</tr>
<tr>
<td>(Z(\to \ell \ell) + \gamma)</td>
<td>(2.0 \pm 0.2 \pm 0.6)</td>
</tr>
<tr>
<td>(\gamma + \text{jet})</td>
<td>(0.4 \pm 0.3)</td>
</tr>
<tr>
<td>Total background</td>
<td>(557 \pm 36 \pm 27)</td>
</tr>
</tbody>
</table>

Data: 521

### CMS

\[
19.6 \, \text{fb}^{-1} (8 \, \text{TeV})
\]

Events / GeV

Data/Bkg. uncertainty

SM + ADD (\(M_b = 2 \, \text{TeV}, n=3\))

<table>
<thead>
<tr>
<th>Process</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z(\to \nu \nu) + \gamma)</td>
<td>(345 \pm 43)</td>
</tr>
<tr>
<td>(W(\to \ell \nu) + \gamma)</td>
<td>(103 \pm 21)</td>
</tr>
<tr>
<td>(W \to \ell \nu)</td>
<td>(60 \pm 6)</td>
</tr>
<tr>
<td>jet (\to \gamma) MisID</td>
<td>(45 \pm 14)</td>
</tr>
<tr>
<td>Beam halo</td>
<td>(25 \pm 6)</td>
</tr>
<tr>
<td>Others</td>
<td>(36 \pm 3)</td>
</tr>
<tr>
<td>Total background</td>
<td>(614 \pm 63)</td>
</tr>
</tbody>
</table>

Data: 630
Many interpretations: dark matter (EFT, simplified models), ADD, compressed SUSY scenario

Similar limits on Dark Matter EFT, slightly better for ATLAS at lower masses and for CMS at large masses
Search for supersymmetry in photon+jets+MET

SUSY-14-004

Selection:

| Trigger | \(\gamma-H_T\) trigger with \(p_T^\gamma \geq 70\) GeV, \(H_T \geq 400\) GeV (using \(p_T^{jets} \geq 40\) GeV, \(|\eta| < 3.0\)) |
|---------|----------------------------------------------------------------------------------------------------------------------------------|
| Photon(s) | \(\geq 1, p_T^{\gamma,\gamma} \geq 110\) GeV, \(|\eta| < 1.4442\) |
| Jet(s) | \(\geq 2, p_T^{jets1,2} \geq 30\) GeV, \(|\eta| < 2.5\) |
| \(H_T\) | \(\geq 500\) GeV (using \(p_T^{jets,\gamma} \geq 40\) GeV, \(|\eta| < 3.0\)) |
| isolated e,\(\mu\) | veto, \(p_T > 15\) GeV, \(|\eta^{e(\mu)}| < 2.5(2.4)\) |
| \(E_T\) | \(E_T \geq 100\) GeV (six intervals in \(E_T\)) |

Background estimation:

- Zy, Wy and \(\gamma t\)t from MC
- QCD from a loose \(\gamma\) CR
- EW from t&p in Zee on CR

<table>
<thead>
<tr>
<th>(E_T) Range [GeV]</th>
<th>[100,120]</th>
<th>[120,160]</th>
<th>[160,200]</th>
<th>[200,270]</th>
<th>[270,350]</th>
<th>[350,(\infty)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD</td>
<td>991(\pm 164)</td>
<td>529(\pm 114)</td>
<td>180(\pm 69)</td>
<td>95.6(\pm 45)</td>
<td>11.7(\pm 12)</td>
<td>9.1(\pm 9)</td>
</tr>
<tr>
<td>EWK</td>
<td>37.3(\pm 4)</td>
<td>42.5(\pm 5)</td>
<td>23.0(\pm 3)</td>
<td>19.2(\pm 2)</td>
<td>7.7(\pm 1.0)</td>
<td>4.1(\pm 0.6)</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>53.6(\pm 27)</td>
<td>72.5(\pm 36)</td>
<td>44.9(\pm 23)</td>
<td>40.1(\pm 20)</td>
<td>19.7(\pm 10)</td>
<td>14.7(\pm 7)</td>
</tr>
<tr>
<td>Background</td>
<td>1082(\pm 166)</td>
<td>644(\pm 119)</td>
<td>248(\pm 73)</td>
<td>155(\pm 50)</td>
<td>39.0(\pm 16)</td>
<td>27.8(\pm 12)</td>
</tr>
<tr>
<td>Data</td>
<td>1286</td>
<td>774</td>
<td>232</td>
<td>136</td>
<td>46</td>
<td>30</td>
</tr>
</tbody>
</table>
Search for supersymmetry in diphoton+MET

ATLAS-CONF-2014-001

Selection:

- Two tight photons with $E_T > 75$ GeV, $E_T^{iso}(0.4) < 4$ GeV
- 5 different SR (strong/weak production for high/low mass bino and a model-independent SR)

Background estimation:

- $Z(\nu\nu)\gamma\gamma$ from MC
- $W(l\nu)\gamma\gamma$ from MC normalized in a $W(l\nu)\gamma\gamma$ CR at lower MET
- QCD BG ($\gamma\gamma$, $\gamma^*+j$): MET template in tight-nontight sample, normalised in MET<60 GeV.
  - SP1 and SP2: too low stat, so made in bins of $M_{eff}$ and extrapolated to SR
- EW BG: from $e\gamma$ CR scaled with $e\rightarrow\gamma$ probability from t&p in $Z(ee)$

<table>
<thead>
<tr>
<th>$\Delta \phi_{\gamma}^{\mu} &lt; \theta$</th>
<th>SP1</th>
<th>SP2</th>
<th>WP1</th>
<th>WP2</th>
<th>MIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \phi_{\gamma}^{\mu} &lt; \theta$</td>
<td>0.5</td>
<td>0.0</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$M_{eff} \rightarrow (H_T) \geq (GeV)$</td>
<td>1500</td>
<td>1800</td>
<td>400</td>
<td>600</td>
<td>0</td>
</tr>
<tr>
<td>$E_T^{miss} \geq (GeV)$</td>
<td>250</td>
<td>150</td>
<td>200</td>
<td>150</td>
<td>250</td>
</tr>
</tbody>
</table>

$\Delta \phi$ w.r.t MET. $M_{eff}$: scalar sum $p_T$'s + MET

<table>
<thead>
<tr>
<th>Background</th>
<th>SP1</th>
<th>SP2</th>
<th>WP1</th>
<th>WP2</th>
<th>MIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD</td>
<td>0.00$^{+0.20}_{-0.00}$</td>
<td>0.22$^{+0.53}_{-0.22}$</td>
<td>0.29 $\pm 0.29$</td>
<td>0.89 $\pm 0.60$</td>
<td>0.73 $\pm 0.53$</td>
</tr>
<tr>
<td>Electroweak</td>
<td>&lt; 0.02</td>
<td>0.02 $\pm 0.02$</td>
<td>0.15 $\pm 0.07$</td>
<td>0.67 $\pm 0.22$</td>
<td>0.24 $\pm 0.10$</td>
</tr>
<tr>
<td>$W(\rightarrow \ell\nu) + \gamma\gamma$</td>
<td>0.03 $\pm 0.02$</td>
<td>0.02 $\pm 0.01$</td>
<td>0.44 $\pm 0.18$</td>
<td>0.74 $\pm 0.27$</td>
<td>0.47 $\pm 0.19$</td>
</tr>
<tr>
<td>$Z(\rightarrow \nu\bar{\nu}) + \gamma\gamma$</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>0.13 $\pm 0.07$</td>
<td>0.08 $\pm 0.04$</td>
<td>0.15 $\pm 0.08$</td>
</tr>
<tr>
<td>Total</td>
<td>0.03$^{+0.20}_{-0.02}$</td>
<td>0.26$^{+0.53}_{-0.22}$</td>
<td>1.01 $\pm 0.36$</td>
<td>2.38 $\pm 0.69$</td>
<td>1.59 $\pm 0.58$</td>
</tr>
<tr>
<td>Observed events</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

GGM: bino-like neutralino, $\tan \beta = 1.5$, $\gamma < 0.1$ mm

\[ \int L \, dl = 20.3 \, fb^{-1}, \, \sqrt{s} = 8 \, TeV \]

ATLAS Preliminary

Higher limit than $\gamma+jets+MET$ in this model
Supersymmetry in diphoton + razor

- At least two photons with $p_T > 30, 22$ GeV and at least one jet $p_T > 40$ GeV

- Use the razor to describe a two-megajet topology coming from the pair production of sparticles each decaying into $X + \text{neutralino}$
  - Form two mega-jets by choosing the ones with lowest sum squared masses

\[
M_R = \sqrt{(|\vec{p}_{j1}| + |\vec{p}_{j2}|)^2 - (p_{z1}^j + p_{z2}^j)^2}
\]

\[
M_T^R = \sqrt{E_T^{\text{miss}}(p_T^{j1} + p_T^{j2}) - \frac{\vec{E}_T}{2}}
\]

- Divide the $(M_R, R^2)$ plane:
  - Signal region: $M_R > 600$ GeV and $R^2 > 0.02$
  - Control region: $M_R > 600$ GeV and $0.01 < R^2 \leq 0.02.$

- Fit the BG in the CR and apply in the SR (normalized to yield)

Limit similar to diphoton + MET in this model
Selection:
- 4 jets or ≥5 jets $p_T>$30 GeV
- ≥2 photons with $E_T>$40, 25 GeV
- $H_T>$60 GeV, $S_T(H_T+MET)>1200$ GeV

Background estimation:
- Fit $S_T$ distribution in Njet=3 sideband
- Normalize in $1100<S_T<1200$ GeV sideband
BSM through $H \rightarrow \gamma X$
Higgs to photon +MET (VBF) [GMSB, NMSSM]

ATLAS-CONF-2015-001

Selection:

- **VBF:** ≥2 jets $p_T$>40 GeV, $m_{jj}$>600 GeV, $\Delta \eta_{jj}$>4.0
- $\geq 1$ photon $E_T$>40 tight photon
  - unconverted (to reduce $e \rightarrow \gamma$)
  - $E_T^{\text{iso}}$(0.4)<5 GeV + $p_T^{\text{tracks}}$(0.2)<0.05$E_T$
  - Between the VBF jets in $\eta$
- **MET**>50 GeV, $\Sigma p_T^{\text{vec}}$(γ+jets)>50 GeV
- $\Delta \phi$(VBF j, MET)>1.4, $\Delta \phi$(γ,MET)<1.8
- Veto lepton, $\leq 1$ non-VBF jet $p_T$>30 GeV

Background estimation:

<table>
<thead>
<tr>
<th>Background</th>
<th>Distributions</th>
<th>Normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W(\rightarrow e\nu)$</td>
<td>$W(\rightarrow e\nu)$ MC with $e \rightarrow \gamma$ misidentification rate from data</td>
<td>Data CR</td>
</tr>
<tr>
<td>$W/Z$ + jets</td>
<td>$W/Z$ + jets MC with jet$\rightarrow \gamma$ misidentification rate from MC</td>
<td>Data CR</td>
</tr>
<tr>
<td>$W\gamma/Z\gamma$</td>
<td>MC</td>
<td>Data CR</td>
</tr>
<tr>
<td>Top and diboson</td>
<td>MC</td>
<td>Data CR</td>
</tr>
<tr>
<td>$\gamma$ + jets and multijet</td>
<td>Data CR</td>
<td></td>
</tr>
</tbody>
</table>

| Total background       | 38.0 ± 2.2 ± 4.5 | 50 |
| Data                   |                  |    |
Supersymmetry through $H \rightarrow \gamma \gamma$


**Selection:**
- $\geq 2$ photons $E_T > 40$, 25 GeV
- $120 < m_{\gamma \gamma} < 131$ GeV
- $\geq 2$ jets $p_T > 30$ GeV
  - loose(80-85%)+medium(50-75%) b-tag
- 3 categories:
  1. Additional loose b-tagged jet
  2. $95 < m_{bb} < 155$ GeV
  3. Others

**Background estimation:**
- Fit in sidebands:
  - $103 < m_{\gamma \gamma} < 118$ GeV
  - $133 < m_{\gamma \gamma} < 163$ GeV

<table>
<thead>
<tr>
<th>Categories</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected background</td>
<td>6.7 ± 1.4</td>
<td>10.5 ± 1.8</td>
<td>29.7 ± 2.8</td>
</tr>
<tr>
<td>observed</td>
<td>6</td>
<td>7</td>
<td>33</td>
</tr>
</tbody>
</table>
Search for FCNC: $t \rightarrow cH(\gamma\gamma)$

Can be greatly enhanced by new physics like heavy vector-like quarks (quark-singlet model) or models of two Higgs doublets with/without flavour conservation:

$$\begin{array}{|c|c|c|c|c|}
\hline
\text{Process} & \text{SM} & \text{QS} & \text{2HDM-III} & \text{FC-2HDM} & \text{MSSM} \\
\hline
 t \rightarrow u\gamma & 3.7 \cdot 10^{-16} & 7.5 \cdot 10^{-9} & - & - & 2 \cdot 10^{-6} \\
t \rightarrow uZ & 8 \cdot 10^{-17} & 1.1 \cdot 10^{-4} & - & - & 2 \cdot 10^{-6} \\
t \rightarrow uH & 2 \cdot 10^{-17} & 4.1 \cdot 10^{-5} & 5.5 \cdot 10^{-6} & - & 10^{-5} \\
t \rightarrow c\gamma & 4.6 \cdot 10^{-14} & 7.5 \cdot 10^{-9} & \sim 10^{-6} & \sim 10^{-9} & 2 \cdot 10^{-6} \\
t \rightarrow cZ & 1 \cdot 10^{-14} & 1.1 \cdot 10^{-4} & \sim 10^{-7} & \sim 10^{-10} & 2 \cdot 10^{-6} \\
t \rightarrow cH & 3 \cdot 10^{-15} & 4.1 \cdot 10^{-5} & 1.5 \cdot 10^{-3} & \sim 10^{-5} & 10^{-5} \\
\hline
\end{array}$$

**ATLAS**

- Two tight isolated photons
- **Hadronic 2\textsuperscript{nd} top:**
  - $\geq 4$ jets, $\geq 1$ b-tagged
  - $M_{jjj}, m_{\gamma\gamma j} \sim$ top mass
- **Leptonic 2\textsuperscript{nd} top:**
  - $\geq 2$ jets, $\geq 1$ b-tagged
  - $m_T > 30$ GeV
  - $m_{\gamma\gamma j}$ and $m_{lvj} \sim$ the top mass
- Fit $m_{\gamma\gamma}$

$B(t \rightarrow cH) < 0.83(0.53)\%$

**CMS**

- Analysis also looking for additional Higgses: multiple SRs (multilepton, diphoton+leptons, diphoton+dilepton...)
- Two photons
- 1 lepton (including tau)
- $120 < m_{\gamma\gamma} < 130$ GeV
- $\geq 1$ b-tagged
- Split in MET bins
- Fit $m_{\gamma\gamma}$ sidebands

$B(t \rightarrow cH) < 0.56(0.65)\%$
Vector-like top through $H \rightarrow \gamma \gamma$

CMS-PAS-B2G-14-003

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hadronic channel</th>
<th>Leptonic channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(\gamma_1)$</td>
<td>$\frac{3}{4}m_{\gamma\gamma}$ GeV</td>
<td>$\frac{1}{2}m_{\gamma\gamma}$ GeV</td>
</tr>
<tr>
<td>$p_T(\gamma_2)$</td>
<td>35 GeV</td>
<td>25 GeV</td>
</tr>
<tr>
<td>$n_{jets}$</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>$H_T$</td>
<td>$\geq 1000$ GeV</td>
<td>$\geq 770$ GeV</td>
</tr>
<tr>
<td>leptons</td>
<td>0</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>b tags</td>
<td>$\geq 1$</td>
<td>-</td>
</tr>
</tbody>
</table>

- **Advantage of $\gamma\gamma$ channel:** can precisely measure $m_{\gamma\gamma}$
  - Search for a narrow resonance centered around the Higgs mass
  - Estimate BG from data sidebands (ttH taken from MC)

```
\begin{tabular}{|c|c|c|}
\hline
Process & Hadronic & Leptonic \\
\hline
TT($m_T = 700$ GeV) & 1.05 & 0.43 \\
\hline
ttH & 0.042 & 0.039 \\
\hline
Background & $0.65^{+0.16}_{-0.13}$ & $0.11^{+0.07}_{-0.03}$ \\
\hline
Observed Data & 2 & 0 \\
\hline
\end{tabular}
```
X → H(bb)H(γγ)

CMS-PAS-HIG-13-032

- X: graviton in extra dimension models, heavy additional Higgs in SUSY,...

Selection:
- ≥ 2 photons
- 100<m_{γγ}<180 GeV
- At least two jets with:
  - 1b-tagged jet (“medium purity”)
  - 2 b-tagged jets (“high purity”)

Two strategies:
- Low-mass region:
  - 260 < m_X < 400 GeV:
  - Use m_{γγ} shape
  - Mass-dependent m_{jj} and m_{γγjj} cuts
    (BG has a peak ~ m_{γγbb} ≈ 300 GeV)
- High-mass region:
  - 400 < m_X < 1100 GeV:
  - Use m_{γγbb} shape
Non-pointing photons
Non-pointing photons in supersymmetry


- GMSB can have a neutralino NLSP with a finite lifetime before decaying into a photon and a gravitino.
- The photons appear delayed and may not point back to the PV.

**Idea:**
- Use the finely segmented ATLAS LAr EM calorimeters:
  - Flight direction using shower spread in the first two layers.
  - Measure $|\Delta z_\gamma| = z_{\text{origin}} - z_{\text{PV}}$.
    - Only barrel photons (resolution worse in the end-caps).
    - Loose photon ID efficiency for signal:
      - 95% for $|z_{\text{origin}}| < 250$ mm down to 75% at $|z_{\text{origin}}| = 700$ mm.
  - Also use the photon arrival time $t_\gamma$ at the calorimeter:
    - From pulse-shape of the 2nd-layer cell with max. energy.
    - $t_\gamma = 0$: prompt photon from the hard collision.
    - Time resolution for large energy deposits is 256 ps.
      - $\approx 220$ ps due to LHC bunch-spread along the beamline.
      - Concentrate on lifetimes above 250 ps.
Non-pointing photons in supersymmetry


Selection:
- 2 loose isolated photons $E_T > 50$ GeV, one in $|\eta| < 1.37$
- MET > 75 GeV
- 2D search in $|\Delta z_\gamma|$ and $t_\gamma$ of the barrel photon (or largest value)
  - Almost completely uncorrelated for prompt backgrounds

**BG estimation:** Templates from low-MET region
Photons as a tool for other BSM searches
An example: the jets+MET SUSY analysis

- **Search for squarks and gluinos in 0-lepton+jets+MET channel**
- **How to estimate the Z(νν)+jets BG?**
  - Select a sample of γ+jets events with $E_T > 130$ GeV
  - Treat the reconstructed photon as contributing to MET
  - For $E_T, \gamma > m_Z$ kinematics very similar to Z+jets
  - Cross section (x BR) ratio $N(\text{photon CR}) \rightarrow N(Z, \text{SR})$: 
  
  $$R_{Z/\gamma} = \frac{d\sigma(Z + \text{jets})/d\pT}{d\sigma(\gamma + \text{jets})/d\pT}$$

- **More stats than Z(\ell\ell) CR...**
Summary

- Very many models of new physics can be probed using photons:
  - supersymmetry, extra dimensions, dark matter, vector-like quarks, technicolour, FCNC, excited quarks, ...
- BSM searches use photons from ~20 GeV up to the TeV scale, converted and unconverted, timing and pointing info, ...
- Many data-driven background estimates: functional form fits, ABCD methods on ID/isolation, t&p on Z(ee) + CR(e), SR variable side-band,...
- They can also be used to control the BG in other BSM searches
- No new physics discovered yet, but run-2 is looming...
- Many analyses will become more sensitive than run-1 very quickly : expect many new results during the next year!
Pflow isolation criteria photon + jet:

- the energy deposited in the single HCAL tower closest to the supercluster position, inside a cone of $\Delta R = 0.15$ centered on the photon direction, must be less than 5% of the energy deposited in that ECAL supercluster;
- the total pT of photons within a cone of $\Delta R = 0.3$, excluding strips of width $\Delta \eta = 0.015$ on each side of the supercluster, must be less than $0.5 \text{ GeV} + 0.005 \text{pT}$
- the total pT of all charged hadrons within a hollow cone of $0.02 < \Delta R < 0.3$ about the supercluster must be less than 0.7 GeV
- the total pT of all neutral hadrons within a cone of $\Delta R = 0.3$ must be less than $0.4 \text{ GeV} + 0.04 \text{pT}$

Pflow isolation criteria photon + MET within a cone of $\Delta R = 0.3$:

- $E_{\text{T}}^{\text{iso}}$(additional photons) $< (0.7 + 0.005 E_{\text{T}})$ GeV
- $E_{\text{T}}^{\text{iso}}$(neutral hadrons) $< (1.0 + 0.04 E_{\text{T}})$ GeV
- $E_{\text{T}}^{\text{iso}}$(charged hadrons) $< 1.5$ GeV
More on razor

\[ M_R = \sqrt{(|\vec{p}_{j1}| + |\vec{p}_{j2}|)^2 - (p_{T1}^j + p_{T2}^j)^2} \]

\[ M_T^R = \sqrt{E_{T}^{miss}(\vec{p}_{T1}^j + \vec{p}_{T2}^j) - E_{T}^{miss} \cdot (\vec{p}_{T1}^j + \vec{p}_{T2}^j)} \]

\[ R = \frac{M_T^R}{M_R} \]

Peaks at \[ M_\Delta = \frac{M_S^2 - M_{LSP}^2}{M_S} \]

Edge at \[ M_\Delta \]

Potential large boost in the beam direction
Transverse boost preferentially small since the mass is large

QCD

Signal

M-H. Genest – BSM w/ photons @ LHC
H->Zgamma

- **ATLAS:**
- **CMS:**
  - [https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13006PubTWiki](https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13006PubTWiki)