Episode Diphoton 750 GeV: A New Force Awakens

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based on W.S. Cho, DK, K. Kong, S.H. Lim, K.T. Matchev, J.C. Park, M. Park
Phenomenon: A New Force Carrier?

- **Diphoton “resonance” search and excess**

- (Mostly) **intended** to discover any resonance **directly** decaying into two photons

- Excess: $m_{\gamma\gamma} \sim 750$ GeV, $\Gamma \sim 45$ GeV

- Local (global) significance: $3.9\sigma (2.3\sigma)$

- Excess: $m_{\gamma\gamma} \sim 760$ GeV, narrow $\Gamma$ favored

- Local (global) significance: $2.6\sigma (2.0\sigma) \rightarrow \sim 3.4\sigma$ local significance at Moriond
Phenomenon: A New Force Carrier?

- The blind men and an elephant

- Limited data statistics, unrevealed information (though more observables were presented at Moriond) + (un)trustable rumors

- Nevertheless, there has been active theoretical effort. → (mostly) standard resonance interpretation
Simple Resonance Interpretations

- Popular, hence most plausible(?) approach
Simple Resonance Interpretations

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- $m_{\gamma\gamma} = m_A \approx 750$ GeV

- Simplest event topology, thus natural(?) interpretation

- Spin 0 or spin 2 resonance (interpreted as a new force carrier) with EFT, 2HDM, SUSY, Extra-Dim, Compositeness, ...
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- Tension?: (rather) large decay width – 6% of the particle mass [ATLAS-CONF-2015-081]
  - cf. $Z$ boson – 2.7%, $W$ boson – 2.6%, $t$ quark – 1.1%, $h$ boson – 0.3% (<2.7%)
  - No other decay modes have been observed.
Large Decay Width Is an Intrinsic Property?

- You might answer

- Well... it is just an early stage. Who cares for now? Let’s wait for more data coming.
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- Well... it is just an early stage. Who cares for now? Let’s wait for more data coming.

- Maybe, yes!
  - Parameter tuning: finding a set of parameters to accommodate all relevant phenomena (as most papers have done so far)
  - Invisible decays/a dark-matter signature
I answered

- Well... it is just an early stage. Who cares for now? Let’s wait for more data coming.

- Maybe, yes!
  - Parameter tuning: finding a set of parameters to accommodate all relevant phenomena (as most papers have done so far)
  - Invisible decays/a dark-matter signature

- Maybe, NO!!
  - “Non-resonance” interpretations: 750 GeV bump may NOT be originating from the decay of a 750 GeV resonance.
“Non-resonance” Interpretations

- Unusual approach

[Cho, DK, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
“Non-resonance” Interpretations

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“A → B → \chi”

“2-step cascade”
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- Diphotoon invariant mass distributions coming from
  - a heavier (than 750 GeV) resonance and
  - its non-minimal decays into the two photons plus (visible or invisible) χ’s
"Non-resonance" Interpretations

Unusual approach

- Diphoton invariant mass distributions coming from
  - a heavier (than 750 GeV) resonance and
  - its non-minimal decays into the two photons plus (visible or invisible) $\chi$'s

- Obviously, more new particles not in loops, (which could be matter particles), are predicted!

[Cho, DK, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
Non-minimal Decay Scenarios

Why those three topologies?

- Study of decay topologies of 2 visibles (here $\gamma$) with # of invisibles (or less clean visibles) $\leq 2$
- Shapes of invariant mass distributions of $v_1, v_2$
  \[ \frac{dN}{dm} \equiv f(m; M_A, M_{B_i}, M_{X_j}) \]
- Investigation on endpoint ($E$), peak ($P$), and curvature ($R_2$)
  \[ E \equiv \max\{m\} \]
  \[ f(m = P) \equiv \max\{f(m)\} \]
  \[ R_2 \equiv -\left(\frac{m^2}{f(m)} \frac{d^2f(m)}{dm^2}\right)_{m=P} \]

Non-minimal Decay Scenarios

Why those three topologies?

- Topologies with both the most singular peak structure and as large $P/E$ as possible
Common Features

- Advantages
  - A broad width naturally arises.

![Graph](image-url)
Common Features

Advantages

- A **broad width** naturally arises.

- The peak position is typically **close to the kinematic endpoint**.
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- A **broad width** naturally arises.

- The peak position is typically **close to the kinematic endpoint**.

- In low statistics, **events near the peak** are likely to emerge.

- Events off the peak are **easily buried** in the SM backgrounds.
Individual Features

- **Antler topology**


  \[
  f(m) \sim \begin{cases} 
  \eta m, & 0 \leq m \leq e^{-\eta}E, \\
  m \ln(E/m), & e^{-\eta}E \leq m \leq E,
  \end{cases}
  \]

  \[
  E = \sqrt{\eta \left(M_{B_1}^2 - M_{\chi_1}^2\right) \left(M_{B_2}^2 - M_{\chi_2}^2\right) / (M_{B_1} M_{B_2})}, \\
  \eta = \cosh^{-1} \left[\left(M_{A}^2 - M_{B_1}^2 - M_{B_2}^2\right) / (2 M_{B_1} M_{B_2})\right].
  \]

  - The shape is **determined by two parameters**, \(E\) and \(\eta\).

  - In our benchmark study, \((A, B_i, \chi_i) = (\text{Scalar, Fermion, Fermion})\)

    \[
    \mathcal{L}_1 \sim AG^{\mu\nu}G_{\mu\nu}, \quad \mathcal{L}_2 \sim A\vec{B}_i B_i, \quad \mathcal{L}_3 \sim \vec{B}_i \sigma^{\mu\nu} \chi_i F_{\mu\nu}
    \]
Individual Features

**Sandwich topology**


\[
f(m) \sim \begin{cases} 
\eta m, & 0 \leq m \leq e^{-\eta}E, \\
\ln(E/m), & e^{-\eta}E \leq m \leq E,
\end{cases}
\]

\[
E = \sqrt{\frac{\eta}{M_A^2 - M_{B_1}^2}(M_{B_2}^2 - M_{\chi_2}^2)/(M_{B_1}M_{B_2})}, \\
\eta = \cosh^{-1} \left[ \frac{(M_{B_1}^2 + M_{B_2}^2 - M_{\chi_2}^2)/(2M_{B_1}M_{B_2})} \right].
\]

- \( f(m) \) is identical to that of the antler, but with different definitions of \( E \) and \( \eta \).

- In our benchmark study, \((A, B_1, B_2, \chi_i) = (U(1) \text{ Vector boson, Scalar, Fermion, Fermion})\)

\[
\mathcal{L}_2 \sim B_1 V^{\mu\nu} F_{\mu\nu}, \mathcal{L}_3 \sim B_1 \overline{B}_2 \chi_1, \mathcal{L}_4 \sim \overline{B}_2 \sigma^{\mu\nu} \chi_2 F_{\mu\nu}
\]
Individual Features

2-step cascade topology

- 2-step cascade topology
  \[ f(m) \sim m, \]
  \[ E = \sqrt{(M_A^2 - M_B^2)(M_B^2 - M_\chi^2)/M_B^2}. \]

- Famous triangular shape

- Only a single parameter, \( E \), determines the shape.

- In our benchmark study, \( (A, B, \chi) = (U(1) \text{ Vector boson}, \text{Scalar}, U(1) \text{ Vector boson}) \)
  \[ \mathcal{L}_2 \sim B A^{\mu \nu} F_{\mu \nu}, \quad \mathcal{L}_3 \sim B \chi^{\mu \nu} F_{\mu \nu} \]
Fit result: antler/sandwich

- Likelihood fit with full model functions, \( f(m) + f_{BG}(m) \), ATLAS cuts used
- Best-fit values: \( \eta = 0.032^{+0.030}_{-0.032}, E = 827^{+30}_{-37} \) GeV \( [\chi^2 = 0.98] \)

[Cho, DK, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
Fit result: 2-step cascade

- Same fit scheme as before
- Best-fit values: \( E = 810^{+20}_{-28} \text{ GeV} \) \([\chi^2 = 0.69]\)
Phenomenology

Other Observables

- $p_T^{\gamma\gamma}$ vs. $m_{\gamma\gamma}$

Antler

Sandwich

2-step cascade

[Cho, DK, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

- Singly-produced primary mother particle is assumed.
Other Observables

- $p_T^{\gamma\gamma}$ vs. $m_{\gamma\gamma}$

**Antler**

Singly-produced primary mother particle is assumed.

- **Antler topology:** small $p_T^{\gamma\gamma}$ is preferred in the region of large diphoton invariant masses.

- Sandwich

- 2-step cascade

[Cho, DK, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
Other Observables

- $p_T^{\gamma\gamma}$ consistency check

$\mathcal{m}_{\gamma\gamma} = [700-840] \text{ GeV}$

Antler scenario shows a similar behavior in the diphoton $p_T$ spectrum of the signal region.

[ATLAS at Moriond 2016]

[Cho, DK, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
Conclusions

Summary

- ATLAS and CMS collaborations have reported an interesting resonance-like excess in the diphoton channel around 750 GeV.
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- Our scenarios can (generally) accommodate a (relatively) large width of the peak, and our model (antler) still seems consistent with the new released data.
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- (Even in the situation where the excess is washed away in the future or the proposed scenarios are ruled out) this can be a good exercise for other signals.
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- ATLAS and CMS collaborations have reported an interesting resonance-like excess in the diphoton channel around 750 GeV.
- While the (standard) resonance interpretation is popular, “non-resonance” interpretations are possible, e.g., cascade decays.
- Our scenarios can (generally) accommodate a (relatively) large width of the peak, and our model (antler) still seems consistent with the new released data.
- (Even in the situation where the excess is washed away in the future or the proposed scenarios are ruled out) this can be a good exercise for other signals.
- Keep open-minded and enjoy the 750 GeV diphoton excess!
Thank you!
Facts and issues

- 750 GeV (ATLAS) vs. 760 GeV (CMS) resonance in (relatively) clean diphoton channel
  → Just an accidental mismatch or not worth ambulance-chasing

- $\gamma\gamma + X$: not so clear with $X$, not unusual

- Only diphoton channel reports an excess
  → No significant excess in $ZZ / WW / ZZ / jj / \ell\ell$ around 750 GeV
  → $\gamma\gamma$ dominant decay? More statistics needed to observe excesses in other channels?

- Production cross section
  → ~15 signal events in ATLAS = ~5fb of cross section times branching fraction
  → Cf. gluon-induced 750 GeV higgs production cross section: $O(1)$ pb
  → Gluon/quark-induced production? ↔ Tension with no excess in the dijet channel
  → Photon-induced production (ex. VBF)? ↔ Tension with perturbativity?

- Rather large decay width!? 
  → invisible decay modes (dark matter)
Parameter & error estimates

- Generating 10K pseudo data set
- via resampling of number-of-events (each bin), according to Poisson distribution with the mean value set to be the original data.
- Conducting the fit procedure for all pseudo data sets.
- Extracting mean values and 1σ confidence interval from the fitted parameter distributions.
- Given low statistics, our fit model (sig+bg) reproduces pseudo data samples well enough.
Parameter & error estimates

ATLAS, $\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
bin width = 40 GeV

-2 ln $L/L_{\text{min}} = 1$
-2 ln $L/L_{\text{min}} = 4$
best fit
Mass projection: antler topology

Symmetric antler assumed, i.e., $B_1 = B_2$, $\chi_1 = \chi_2$

[Cho, DK, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
Mass projection: sandwich topology

Same invisible particles assumed, i.e., $\chi_1 = \chi_2$

[Cho, DK, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
Mass projection: 2-step cascade topology

[Cho, DK, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
**$p_T$ vs. invariant mass: antler topology**

- In the rest frame of particle A

  - To reach the maximum invariant mass, two photons should be back-to-back, i.e., **no significant diphoton transverse momentum**.
  
  - In the rest frame of each $B$ particle, photon and $\chi$ are emitted back-to-back.
  
  - For the events having the maximum invariant mass, the two $\chi$'s are likely to be back-to-back, i.e., **no significant transverse momentum of two $\chi$'s**.
Distinguishing scenarios using energy spectrum

- High statistics assumed
- Distributions with basic cuts
  - Resonance: energy peak = half the $m_{\gamma\gamma}$ resonance peak
  - Antler (red): (in general) energy peak ≠ half the $m_{\gamma\gamma}$ resonance peak [Agashe, Franceschini and DK, arXiv:1209.0772]
  - Sandwich (green) and 2-step cascade (blue): could develop a double-bump structure [Agashe, Franceschini and DK, arXiv:1309.4776]

[Cho, DK, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
Improvement with spin effect

- Non-trivial spin correlation distorts the shape.
- Certain choices of spin correlation would develop more favorable shape by repopulating more events in a narrow region around the peak!

Antler/sandwich

2-step cascade