# The Blind Men and an Elephant: an Alternative Interpretation for the Diphoton 750 GeV Excess


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New Physics Interpretations at the LHC

Argonne National Laboratory, May 2, 2016

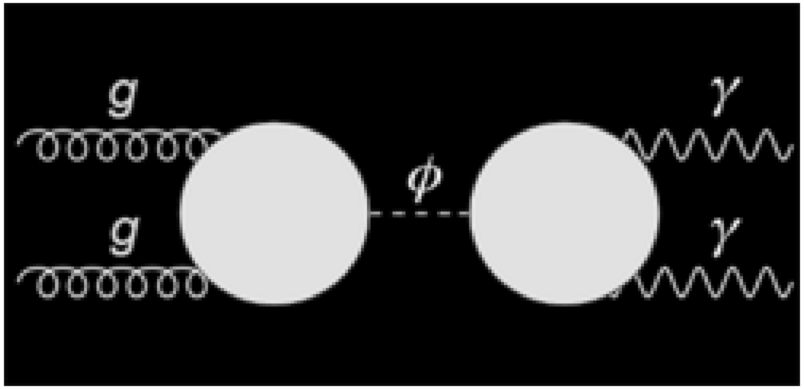
based on W.S. Cho, DK, K. Kong, S.H. Lim, K.T. Matchev, J.C. Park, M. Park
Phys. Rev. Lett. **116**, 151805 (2016) [arXiv:1512.06824]

# Synopsis: Explaining a 750 GeV Bump

Print

April 12, 2016

Theorists try to explain data from the LHC that could be hinting at the existence of new particles.




Y. Nakai et al., Phys. Rev. Lett. (2016)

Late last year, two collaborations at the LHC reported hints that proton-proton collisions created more photon pairs (diphotons) than expected with energies of about 750 GeV (in the diphoton's rest frame). Such a "bump" in the diphoton spectrum is very much like the signal that led to the discovery of the Higgs boson. The difference is that no one was expecting another such bump. If confirmed, it would imply the existence of surprising new particles.

This exciting hint has generated many theory papers (see *Physical Review Letters'* Editorial: "Theorists React to the CERN 750 GeV Diphoton Data"). Most of the models proposed contain a new 750 GeV boson—6 times heavier than the Higgs boson—plus some other particles, such as new fermions that would couple the new boson to pairs of photons and to pairs of gluons generated by the LHC's colliding protons.

Now, a quartet of papers, appearing in the same issue of *Physical Review Letters*, attempt to explain the origin of the 750 GeV signal. Three papers are centered around some new 750 GeV boson: a pion-like boson associated with a new type of strong force (Y. Nakai, R. Sato, and K. Tobioka), a Higgs-like boson that couples to new kinds of fermions (G. Li *et al.*), or a boson that is the supersymmetric partner of a hypothetical fermion called the goldstino (C. Petersson and R. Torre). The fourth paper (W. S. Cho *et al.*) explores the possibility that the diphoton excess is not due to a 750 GeV particle at all, but to some even heavier particles that decay via a cascade to lighter particles along with photon pairs of about 750 GeV.

750 GeV Diphoton Excess May Not Imply a 750 GeV Resonance
Won Sang Cho, Doojin Kim, Kyoungchul Kong, Sung Hak Lim, Konstantin T. Matchev, Jong-Chul Park, and Myeonghun Park
Phys. Rev. Lett. 116, 151805 (2016)
Published April 12, 2016

Pseudoscalar Decaying Only via Loops as an Explanation for the 750 GeV Diphoton Excess
Gang Li, Ying-nan Mao, Yi-Lei Tang, Chen Zhang, Yang Zhou, and Shou-hua Zhu
Phys. Rev. Lett. 116, 151803 (2016)
Published April 12, 2016

750 GeV Diphoton Excess from the Goldstino Superpartner
Christoffer Petersson and Riccardo Torre
Phys. Rev. Lett. 116, 151804 (2016)
Published April 12, 2016

Footprints of New Strong Dynamics via Anomaly and the 750 GeV Diphoton
Yuichiro Nakai, Ryosuke Sato, and Kohsaku Tobioka
Phys. Rev. Lett. 116, 151802 (2016)
Published April 12, 2016

*NATURE* | NEWS

# Zoo of theories showcased in publications on LHC anomaly

Four published papers offer diverse explanations for a possible new particle.

Davide Castelvecchi

20 April 2016

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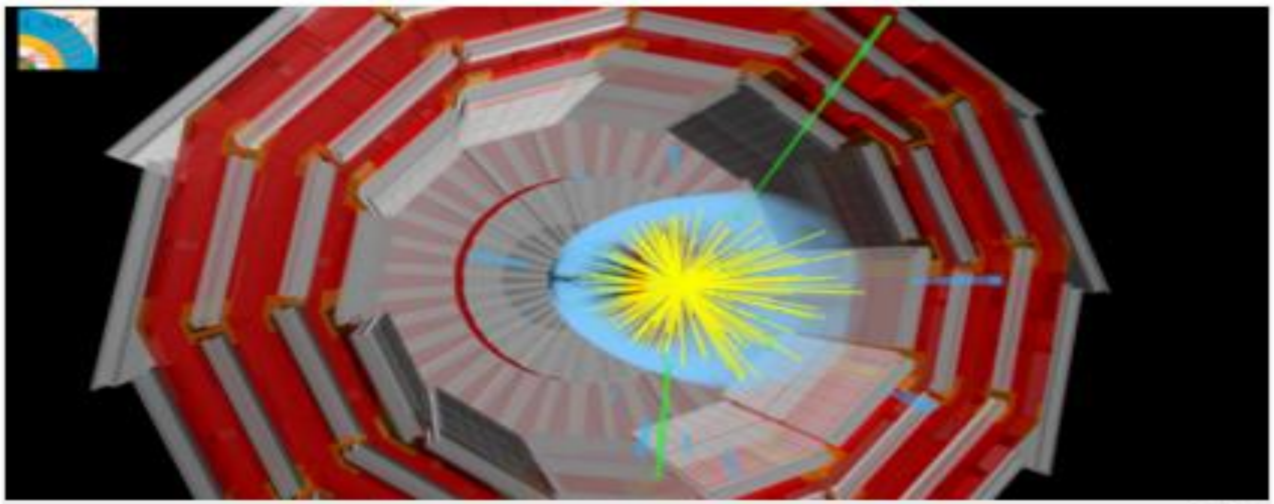


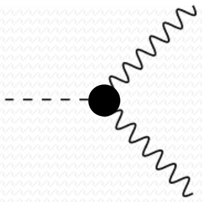
CERN

An excess of particle collisions that produce photon pairs at the LHC has inspired more than 300 papers.

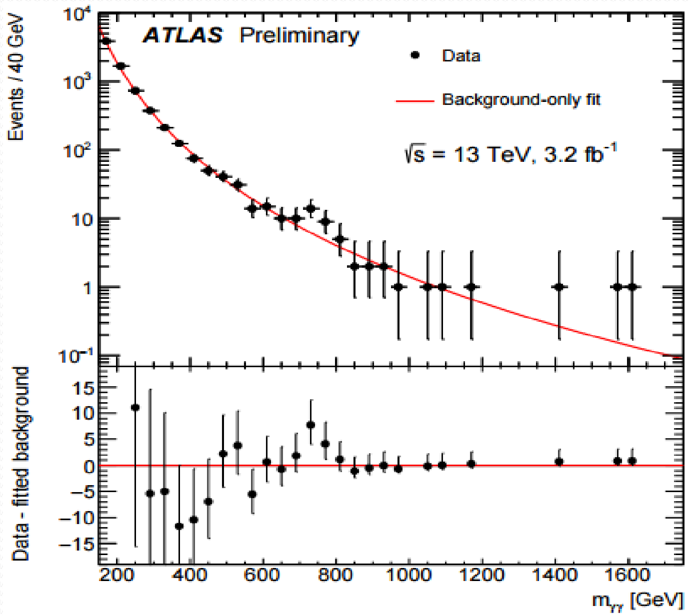
The most surprising of the four papers, according to Peskin, comes from Doojin Kim of the University of Florida in Gainesville and six collaborators, three of whom are theorists on the CMS team. They propose[5] that there is no particle with a mass of 750 GeV. Instead, the two photons could represent part of the debris produced by the decay of a potentially much more massive particle.

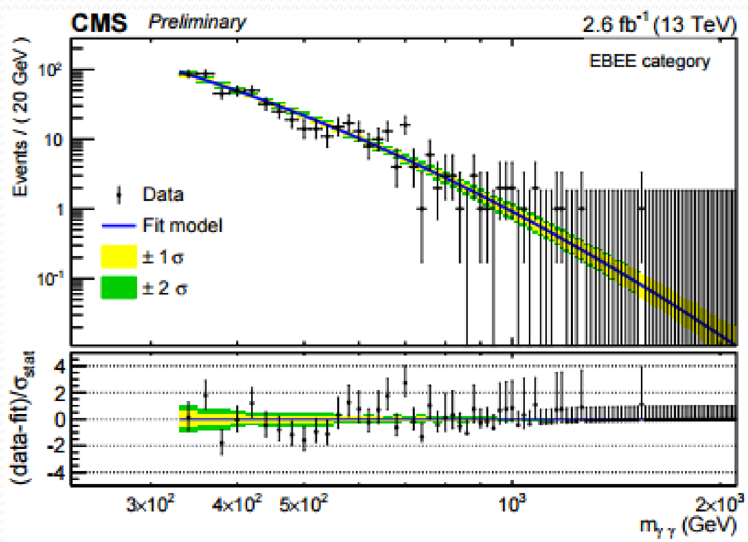
# Phenomenon

## Diphoton "resonance" search and excess



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



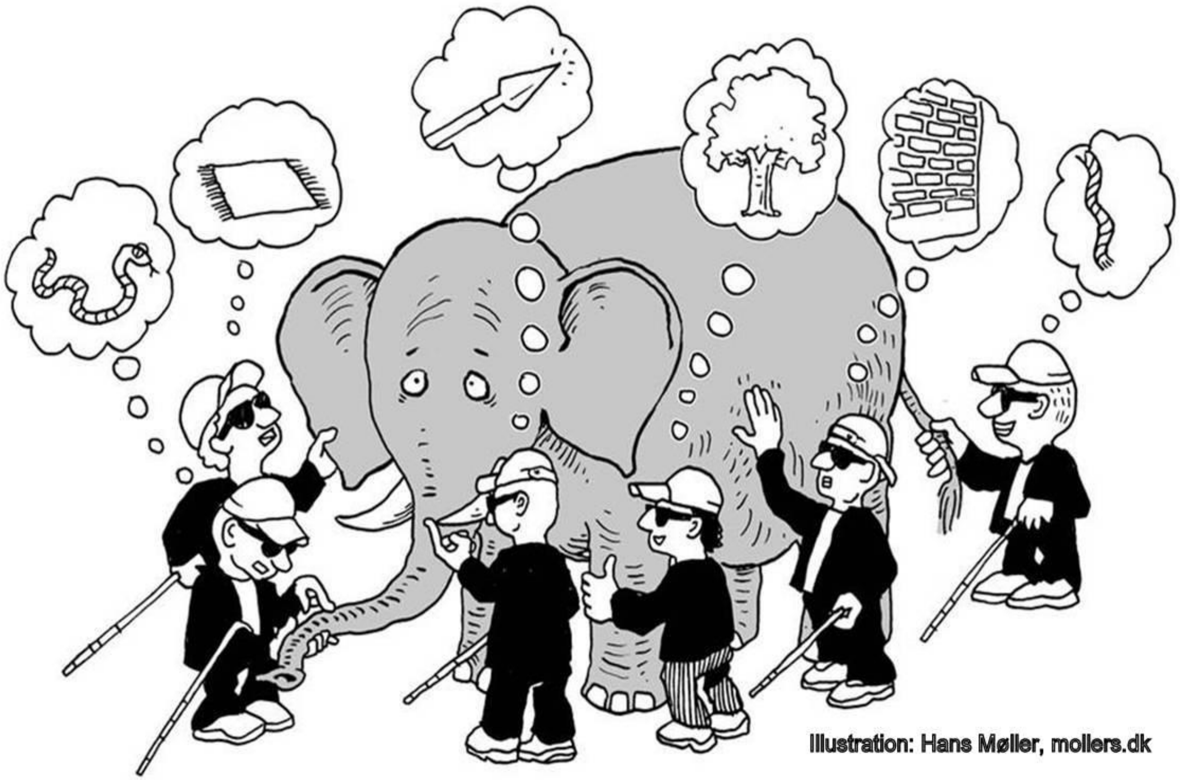




- Excess: $m_{\gamma\gamma}$~750 GeV, Γ~45 GeV
- Local (global) significance: $3.9\sigma(2.3\sigma)$
- Excess: $m_{\gamma\gamma}$~760 GeV, narrow Γ favored
- Local (global) significance: $2.6\sigma(2.0\sigma) \rightarrow$ ~$3.4\sigma$ local significance at Moriond

# Phenomenon

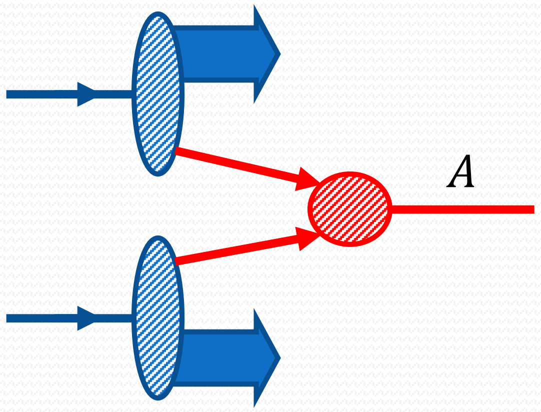
## The blind men and an elephant

- **Limited data collected**, **unrevealed information** (though more observables were presented at Moriond)
- (Un)trustable rumors
- Theorists never get disappointed. → **Diphoton "Syndrome"**



# Simple Resonance Interpretations

- Popular, hence most plausible(?) approach



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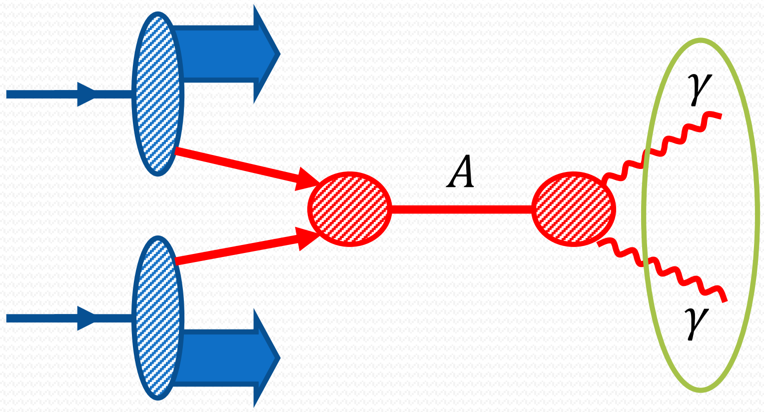


- ❑ $m_{\gamma\gamma} = m_A \approx 750$ GeV
- ❑ Simplest event topology, thus natural(?) interpretation
- ❑ **Spin 0** or spin 2 resonance interpretations with EFT, 2HDM, SUSY, Extra-Dim, Compositeness, …

# Simple Resonance Interpretations

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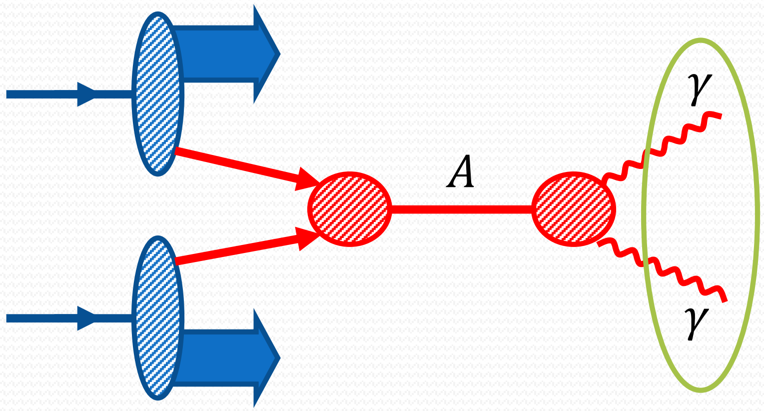


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- ❑ **Spin 0** or spin 2 resonance interpretations with EFT, 2HDM, SUSY, Extra-Dim, Compositeness, …

- ❑ 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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- ❑ 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

# Large Decay Width Is an Intrinsic Property?

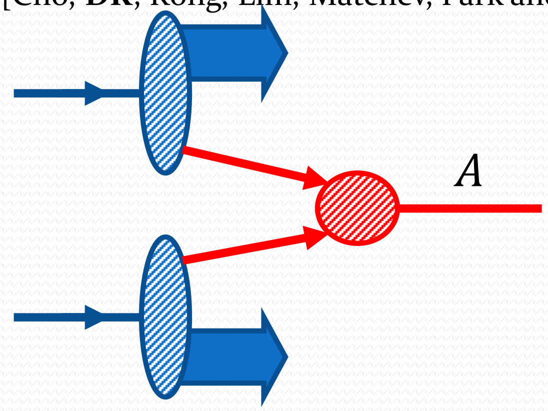
## I answered

- ❑ 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, hence most surprising(?!) approach (as per Peskin)

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



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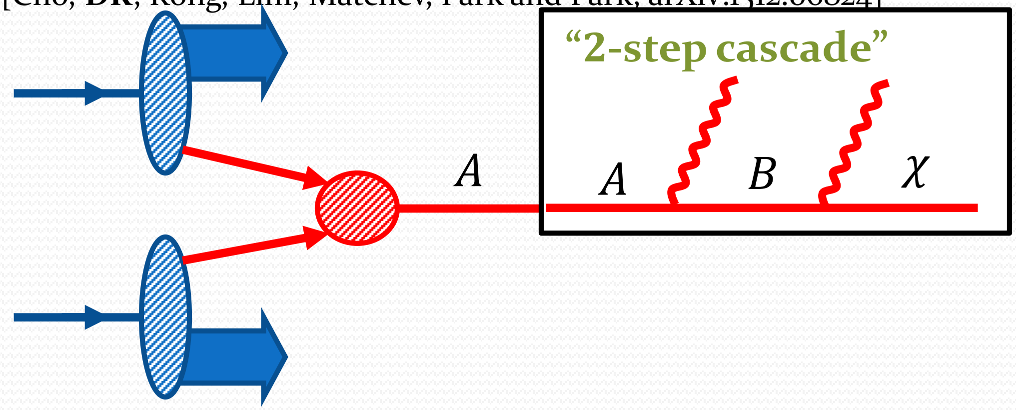

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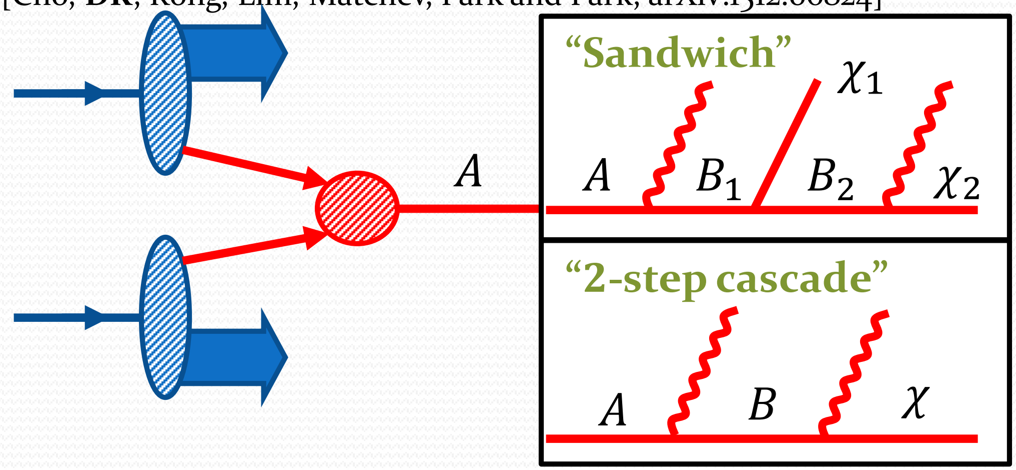

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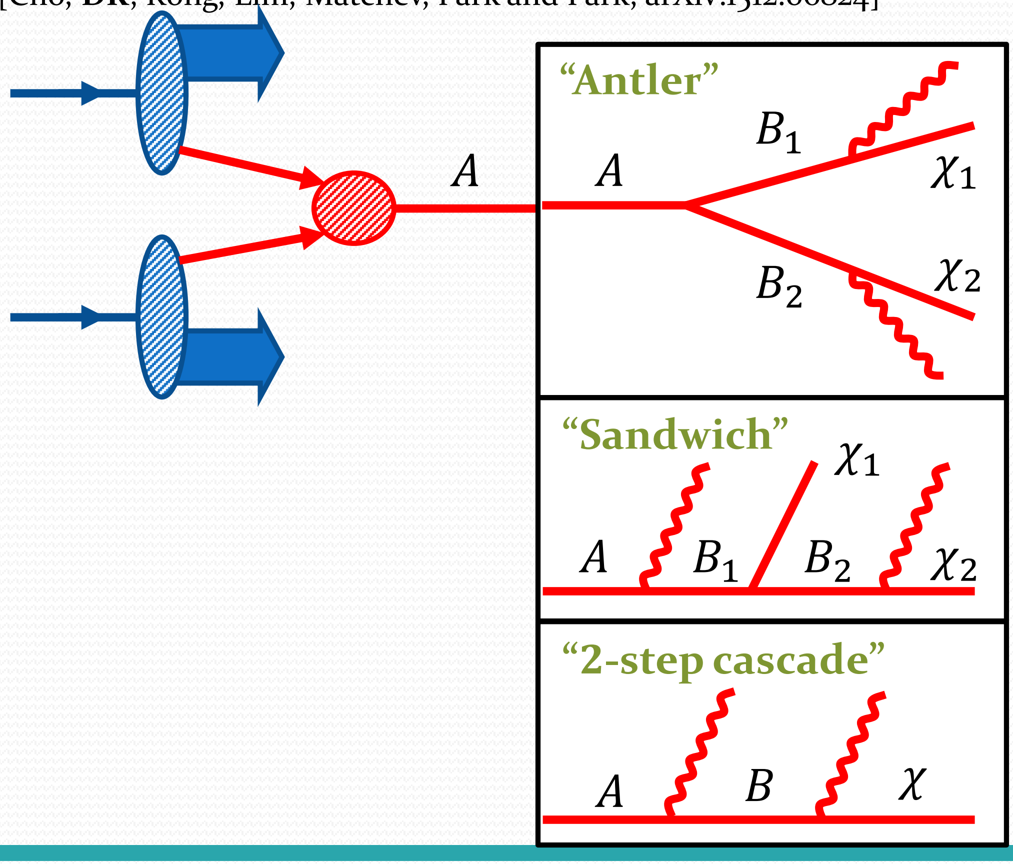

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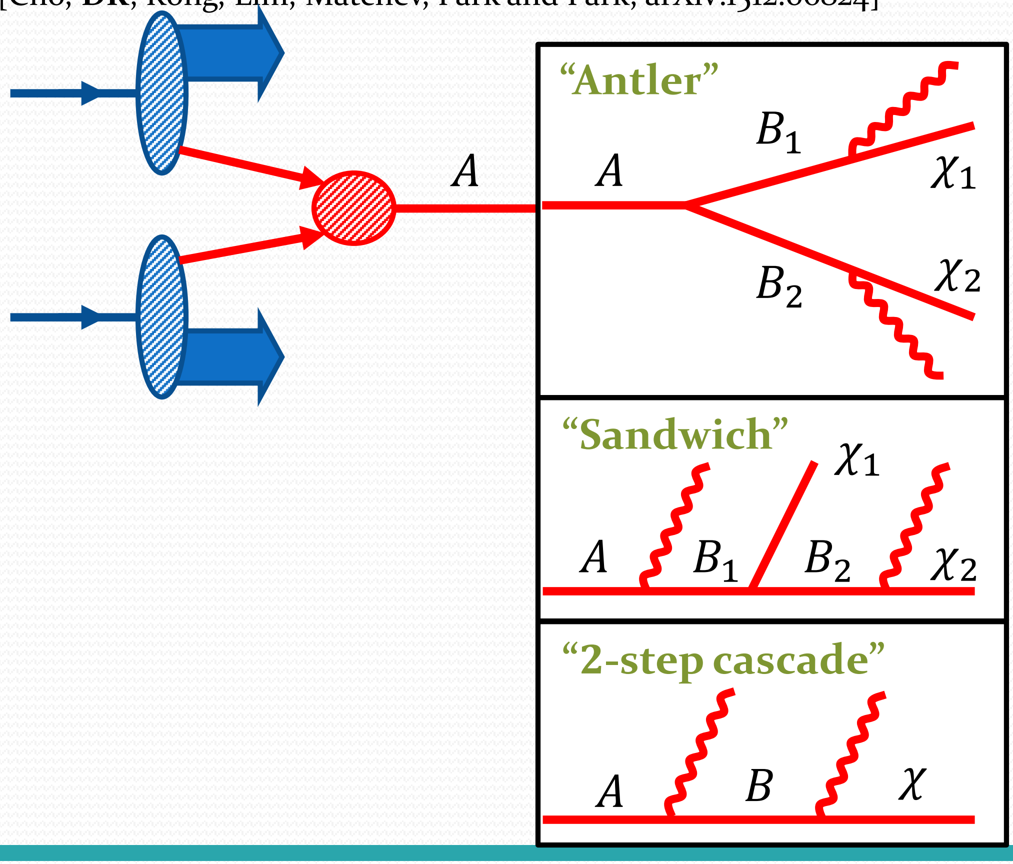


- ❑ Diphoton invariant mass distributions coming from
  - ✓ a **heavier** (than 750 GeV) **resonance** and
  - ✓ its **non-minimal decays** into the **two photons plus (visible or invisible)** $\chi$**’s**

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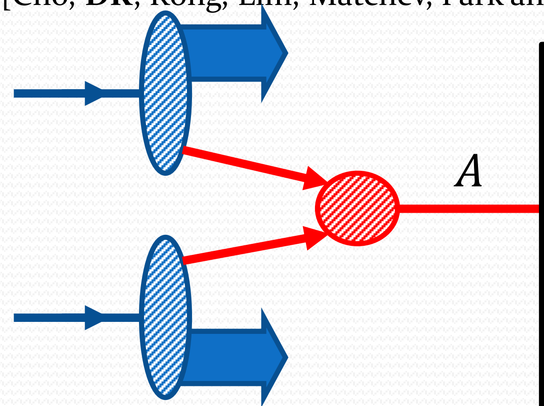
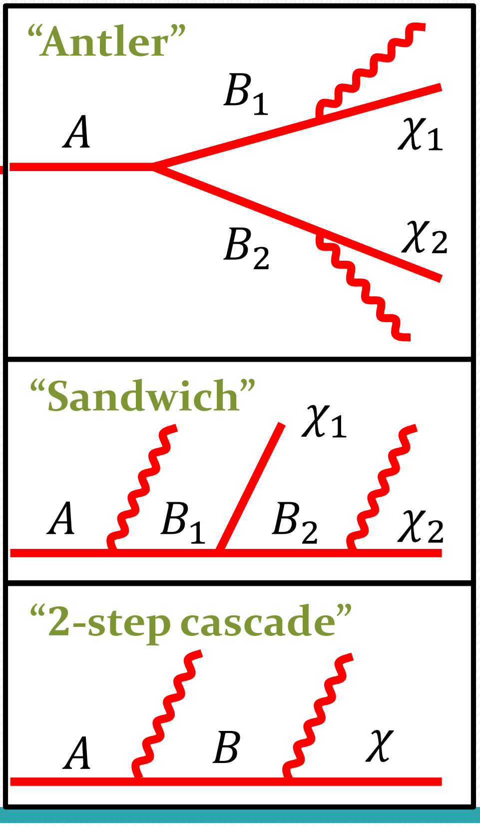



- ❑ Diphoton invariant mass distributions coming from
  - ✓ a **heavier** (than 750 GeV) **resonance** and
  - ✓ its **non-minimal decays** into the **two photons plus (visible or invisible) $\chi$'s**
- ❑ Obviously, **more new particles** (not in loops) are predicted!

# 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 $v_1, v_2$

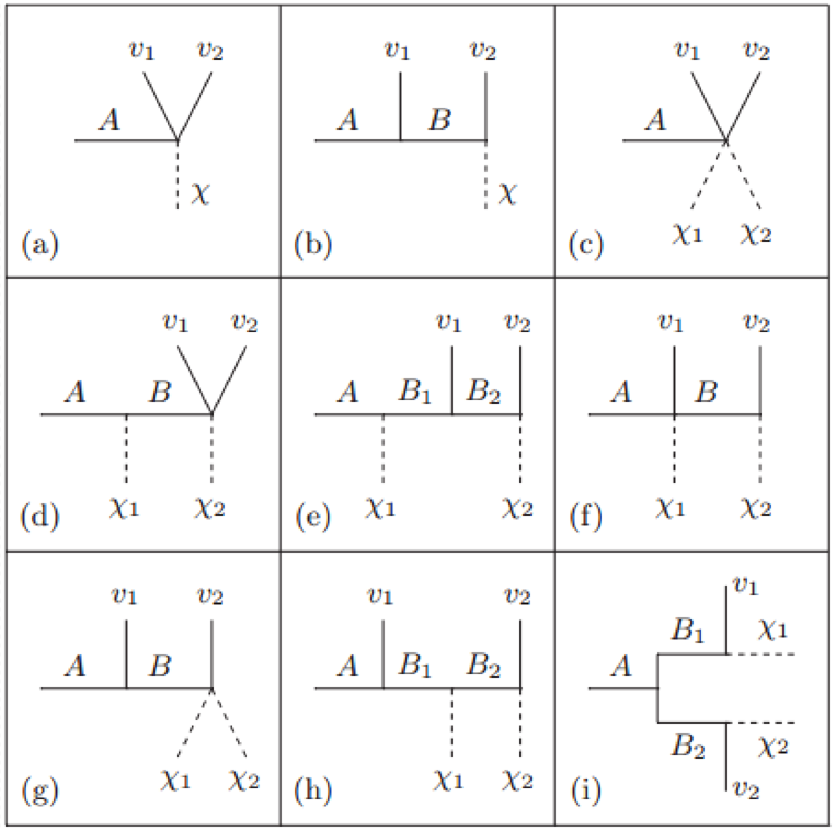
$$\frac{dN}{dm} \equiv f(m;\ M_A, M_{B_i}, M_{\chi_j})$$

- Investigation on endpoint ($E$), peak ($P$), and curvature ($R_2$)

$$E \equiv \max\{m\}$$

$$f(m = P) \equiv \max\{f(m)\}$$

$$R_2 \equiv -\left(\frac{m^2}{f(m)} \frac{d^2 f(m)}{dm^2}\right)_{m=P}$$

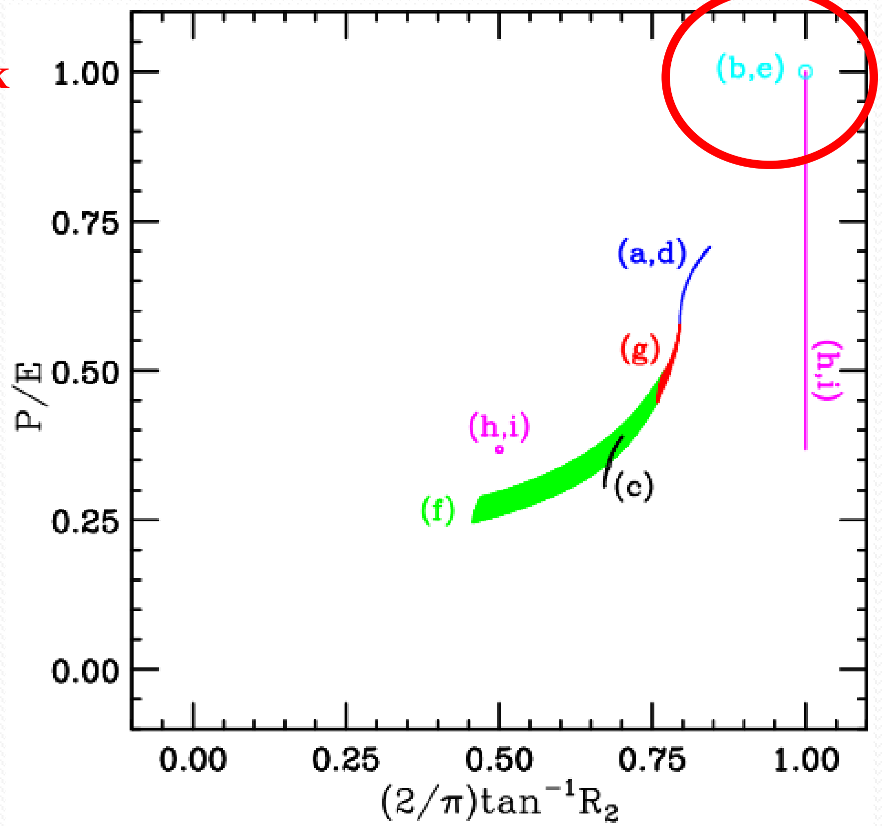



[Cho, **DK**, Matchev and Park, PRL (2014), arXiv:1206.1546]

# Non-minimal Decay Scenarios

## Why those three topologies?

- Topologies with both the **most singular peak** structure and **as large $P/E$ as** possible
  - ✓ **Topology (h): "Antler"** [Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
  - ✓ **Topology (i): "Sandwich"** [Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
  - ✓ **Topologies (b), (e): "2-step cascade"** [Knapen, Melia, Pappuci and Zurek, arXiv:1512.04928, Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]
  - ✓ Cf.) Topology (a): "3-body decay" [Bernon and Smith, arXiv:1512.06113, An, Cheung and Zhang, arXiv:1512.08378]

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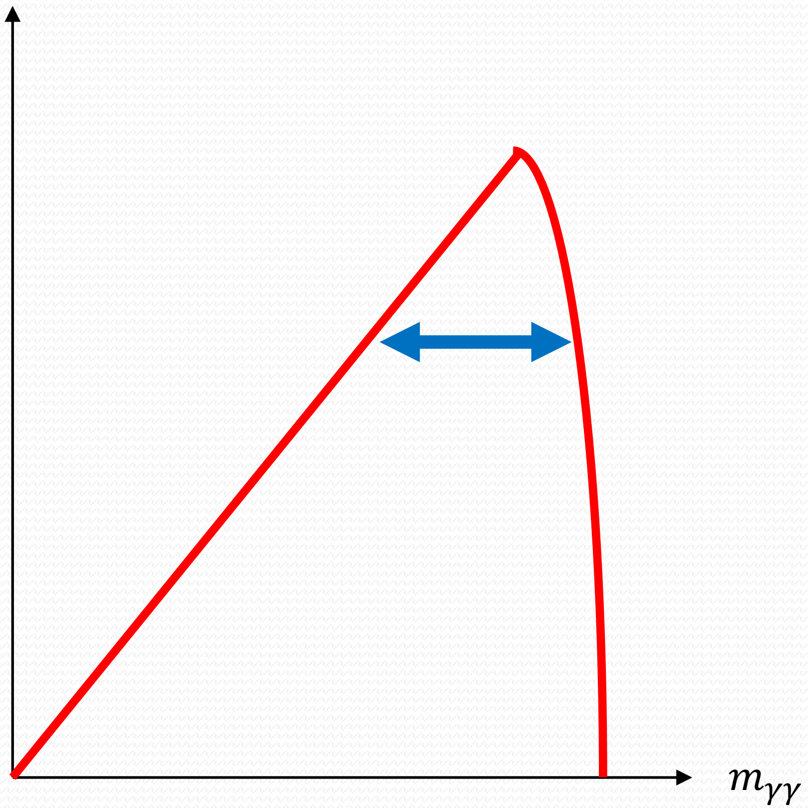
# Common Features

## Advantages

- A **broad width** naturally arises.



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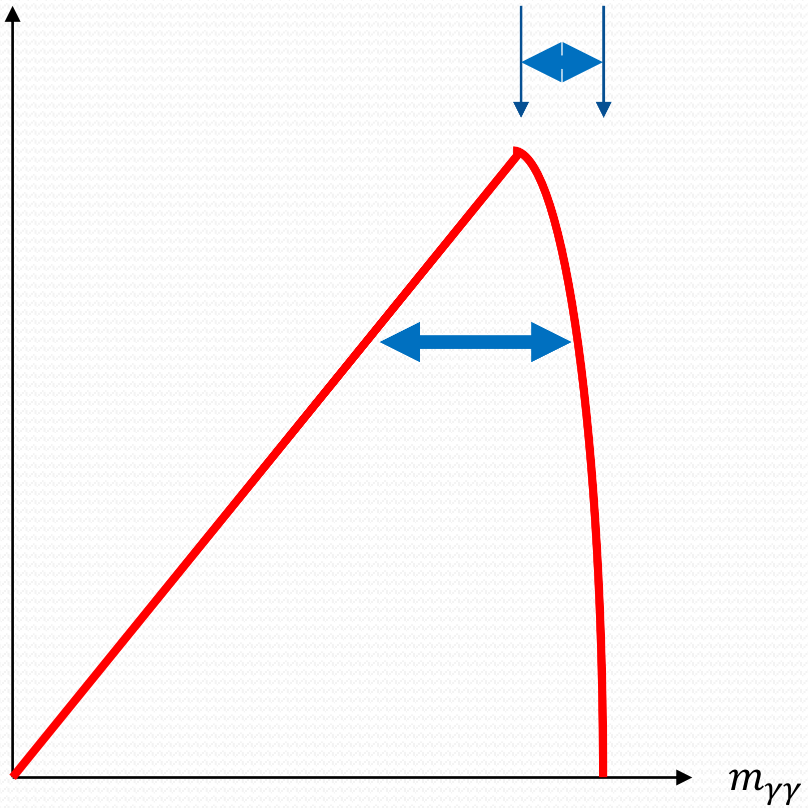
- The peak position is typically **close to the kinematic endpoint**.



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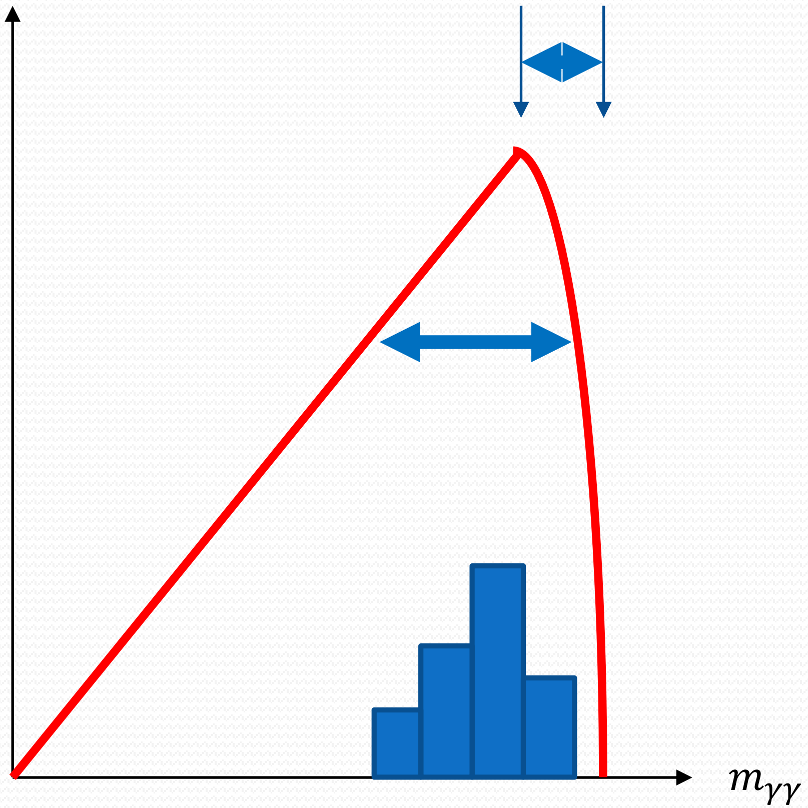
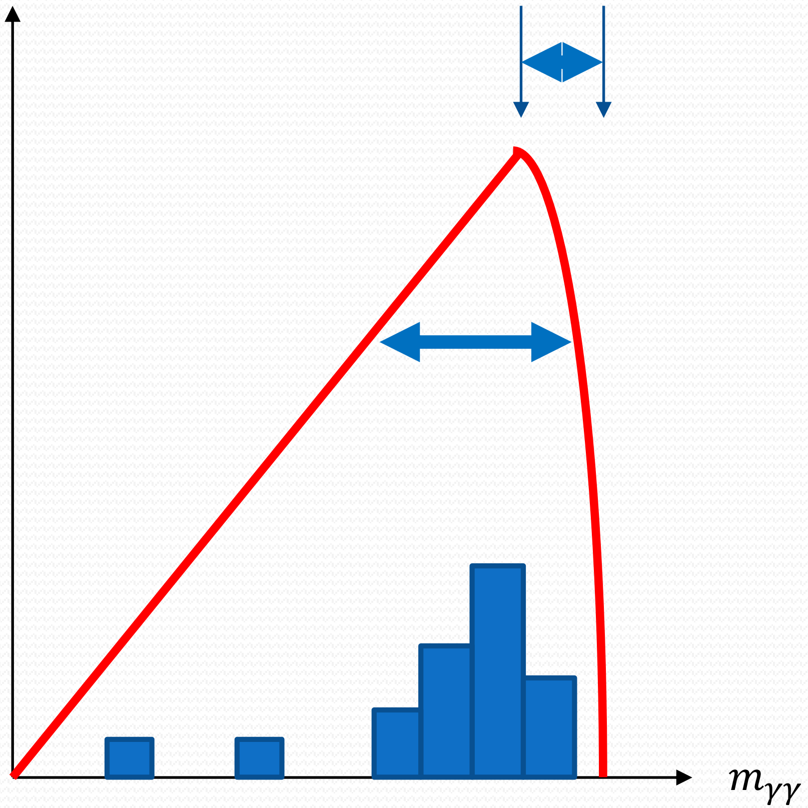


# Common Features

## Advantages

- 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.

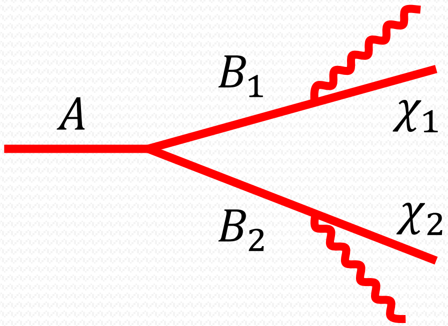


# Individual Features

## Antler topology

- Antler topology [Han, Kim and Song, arXiv:0906.5009, Cho, **DK**, Matchev and Park, arXiv:1206.1546]

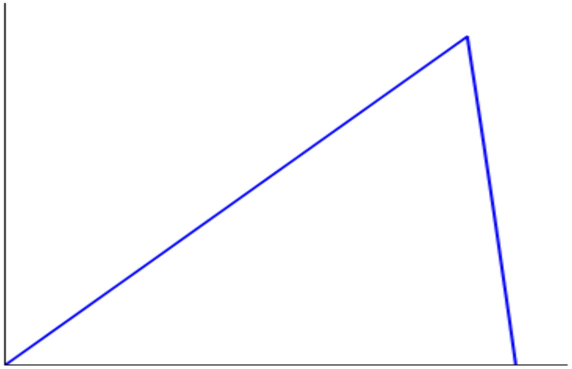
$$f(m) \sim \begin{cases} \eta\, m\,, & 0 \le m \le e^{-\eta} E, \\ m \ln(E/m)\,, & e^{-\eta} E \le m \le E, \end{cases}$$




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

- The shape is **determined by two parameters**, $E$ and $\eta$.
- In our benchmark study, $(A, B_i, \chi_i) =$ (Scalar, Fermion, Fermion)

$$\mathcal{L}_1 \sim A G^{\mu\nu} G_{\mu\nu},\ \mathcal{L}_2 \sim A \bar{B}_i B_i,\ \mathcal{L}_3 \sim \bar{B}_i \sigma^{\mu\nu} \chi_i F_{\mu\nu}$$

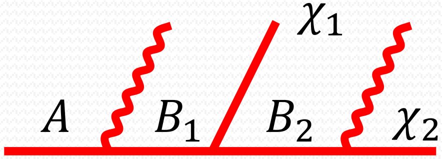


# Individual Features

## Sandwich topology

- Sandwich topology [Agashe, **DK**, Toharia and Walker, arXiv:1003.0899, Cho, **DK**, Matchev and Park, arXiv:1206.1546]

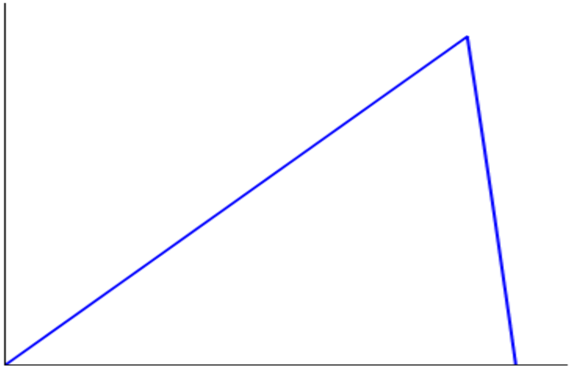
$$f(m) \sim \begin{cases} \eta m\,, & 0 \le m \le e^{-\eta}E, \\ m\ln(E/m)\,, & e^{-\eta}E \le m \le E, \end{cases}$$




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

- $f(m)$ 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) Vector boson, Scalar, Fermion, Fermion)

$$\mathcal{L}_2 \sim B_1 V^{\mu\nu}F_{\mu\nu},\ \mathcal{L}_3 \sim B_1\bar{B}_2\chi_1,\ \mathcal{L}_4 \sim \bar{B}_2\sigma^{\mu\nu}\chi_2 F_{\mu\nu}$$



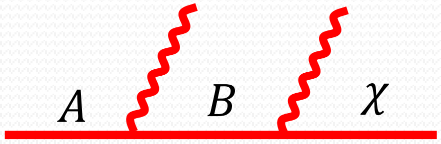
# Individual Features

## 2-step cascade topology

- 2-step cascade topology

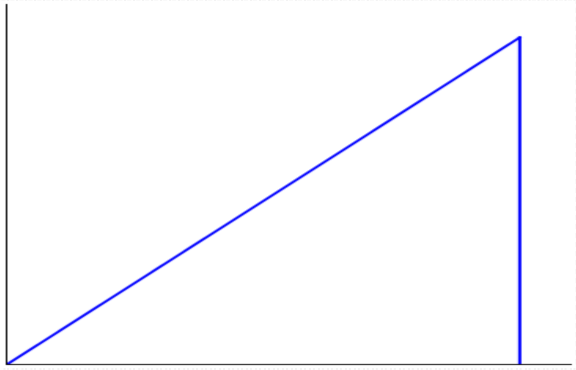
$$f(m) \sim m,$$

$$E = \sqrt{(M_A^2 - M_B^2)(M_B^2 - M_\chi^2)/M_B^2}\,.$$



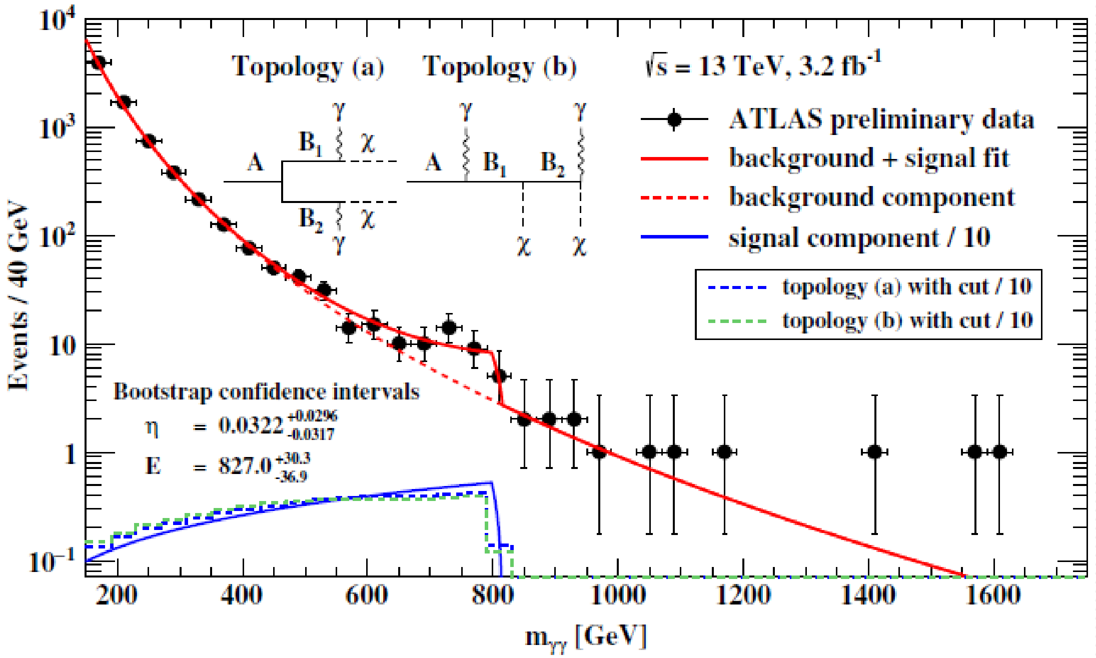

- Famous triangular shape
- Only a **single parameter, *E*, determines the shape**.
- In our benchmark study, $(A, B, \chi) =$ (U(1) Vector boson, Scalar, U(1) Vector boson)

$$\mathcal{L}_2 \sim B A^{\mu\nu} F_{\mu\nu},\ \ \mathcal{L}_3 \sim B \chi^{\mu\nu} F_{\mu\nu}$$



# Data Analysis

## Fit result: antler/sandwich

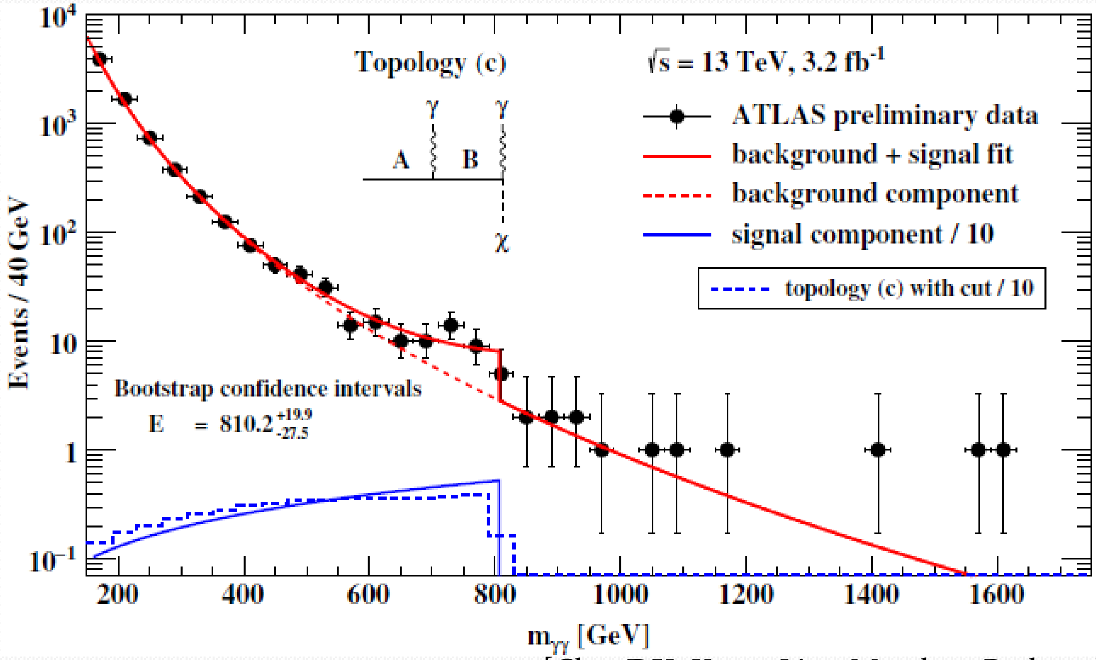



[Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

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

# Data Analysis

## Fit result: 2-step cascade

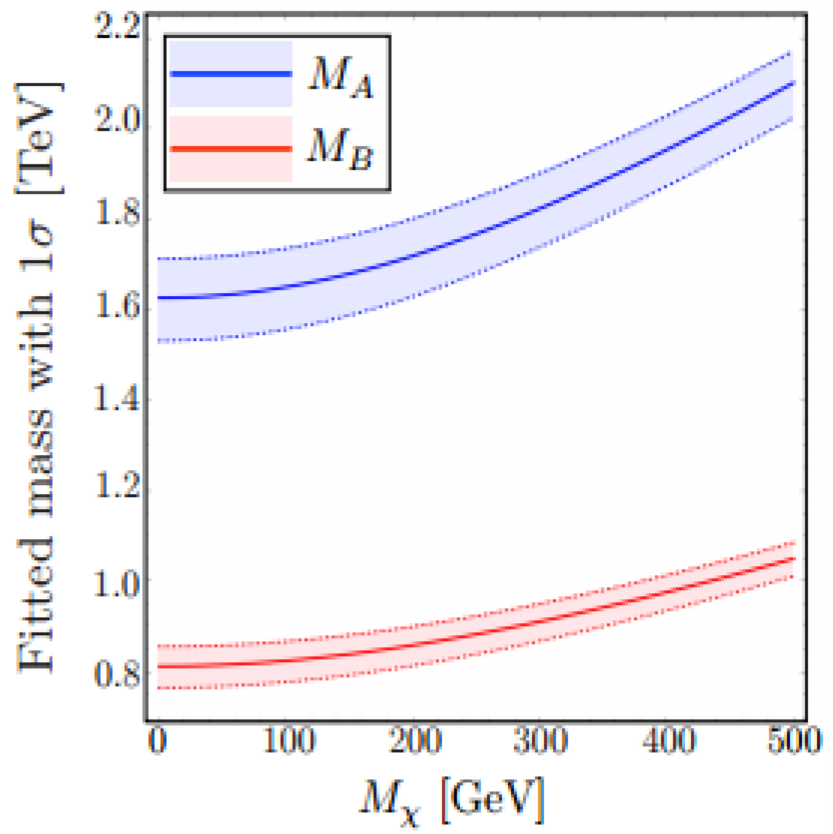


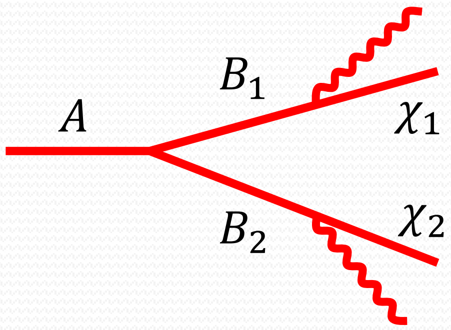

[Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

- Same fit scheme as before
- Best-fit values: $\boldsymbol{E = 810^{+20}_{-28}}$ **GeV** $[\chi^2 = 0.69]$

# Mass Projection

## Antler topology



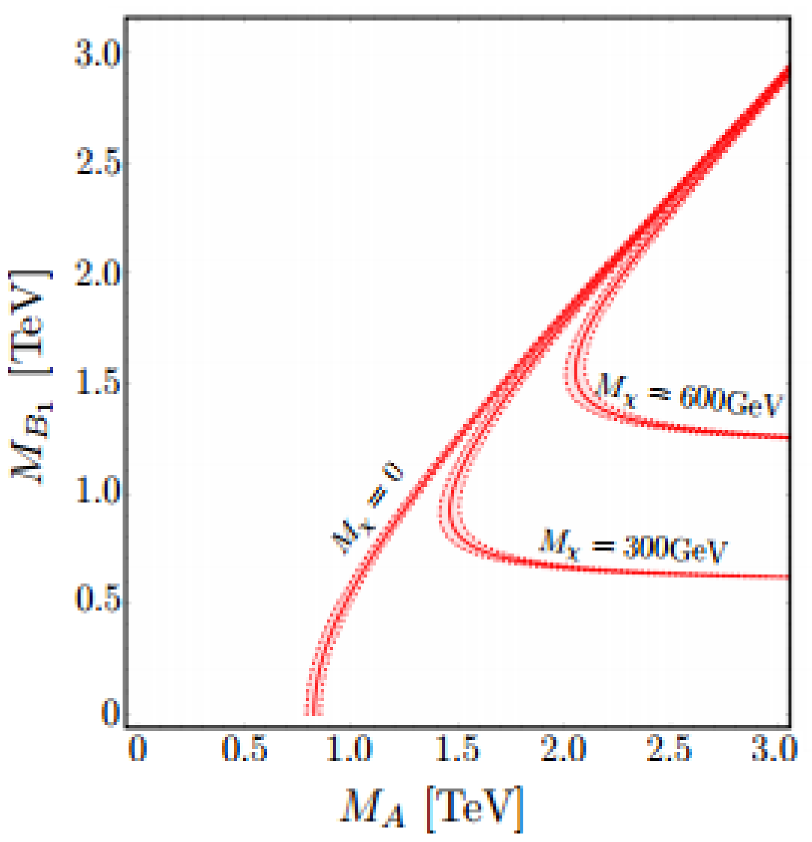



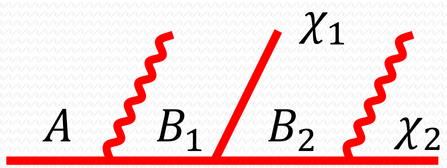

- Symmetric antler assumed, i.e., $B_1 = B_2$, $\chi_1 = \chi_2$

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

# Mass Projection

## Sandwich topology



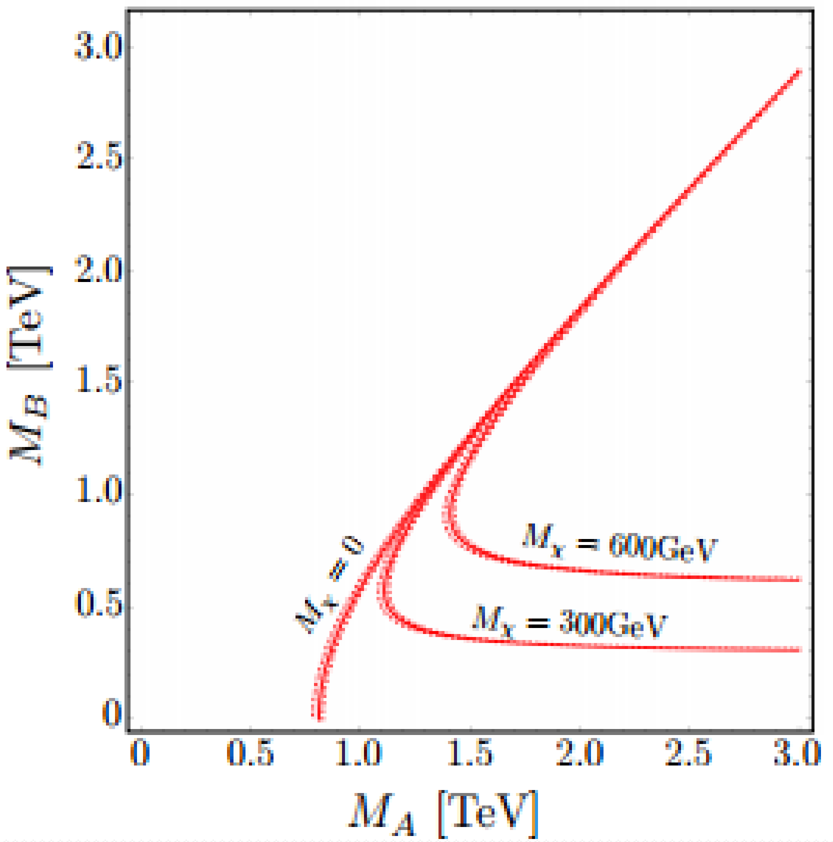



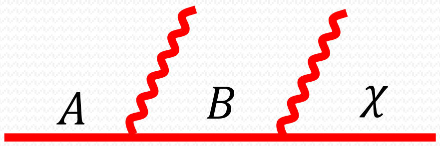

- Same invisible particles assumed, i.e., $\chi_1 = \chi_2$

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

# Mass Projection

- **2-step cascade topology**



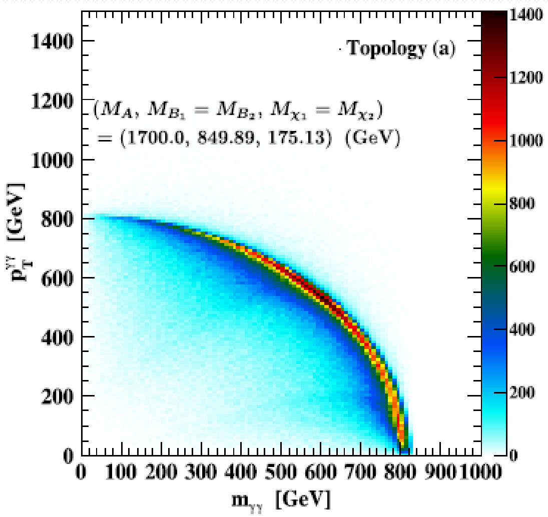




[Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

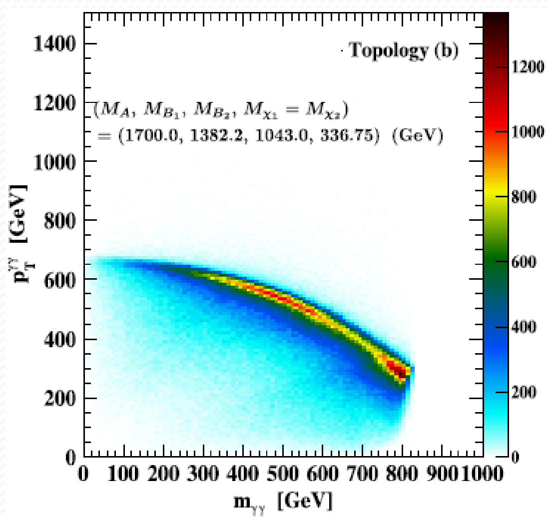
# Other Observables

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

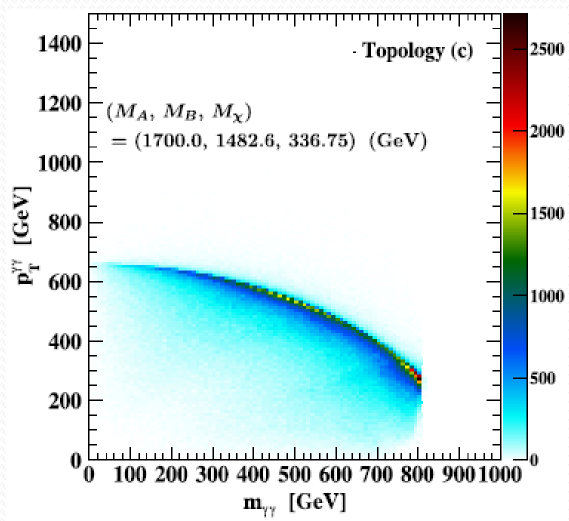
Antler




Sandwich




2-step cascade



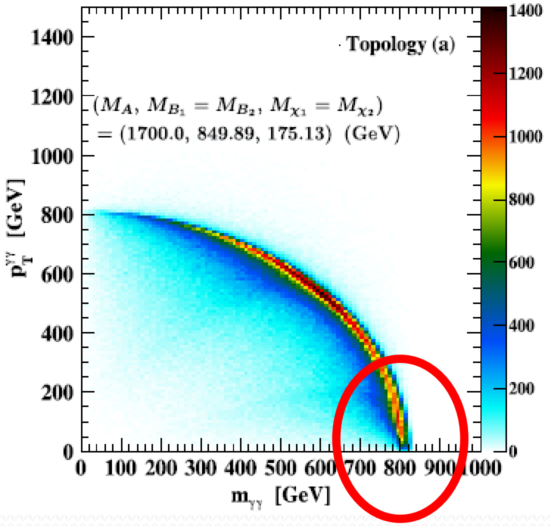

[Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

- Singly-produced primary mother particle is assumed.

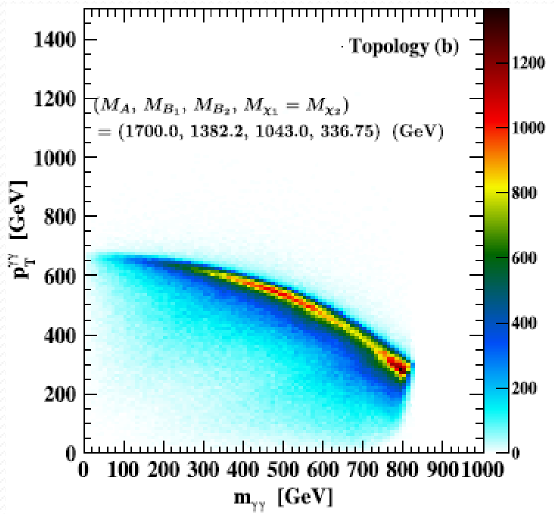
# Other Observables

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

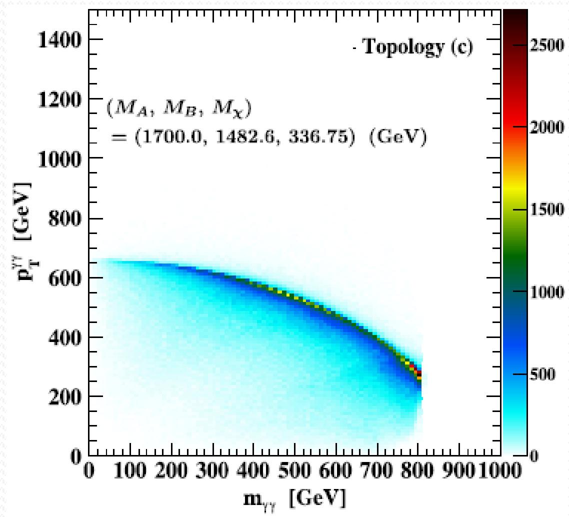
Antler




Sandwich




2-step cascade

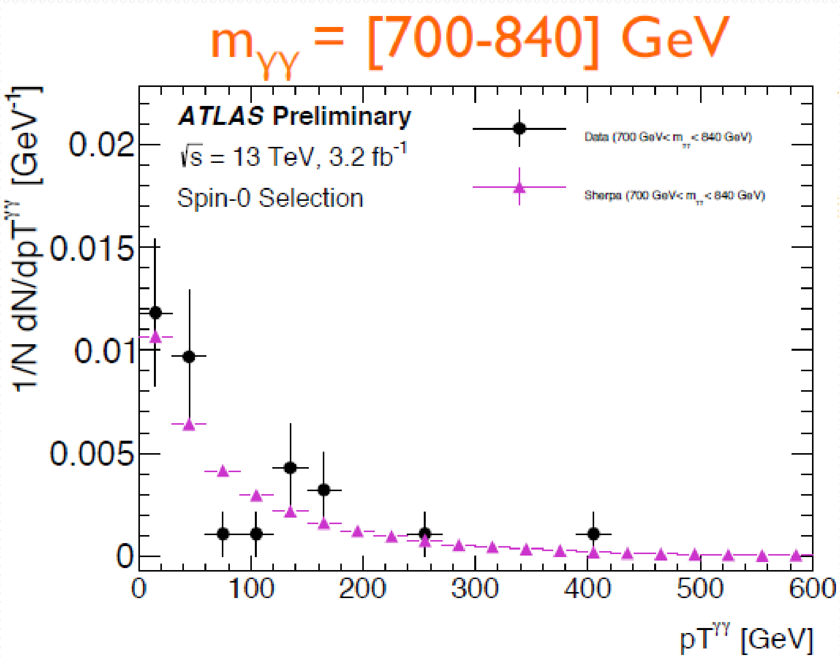



[Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

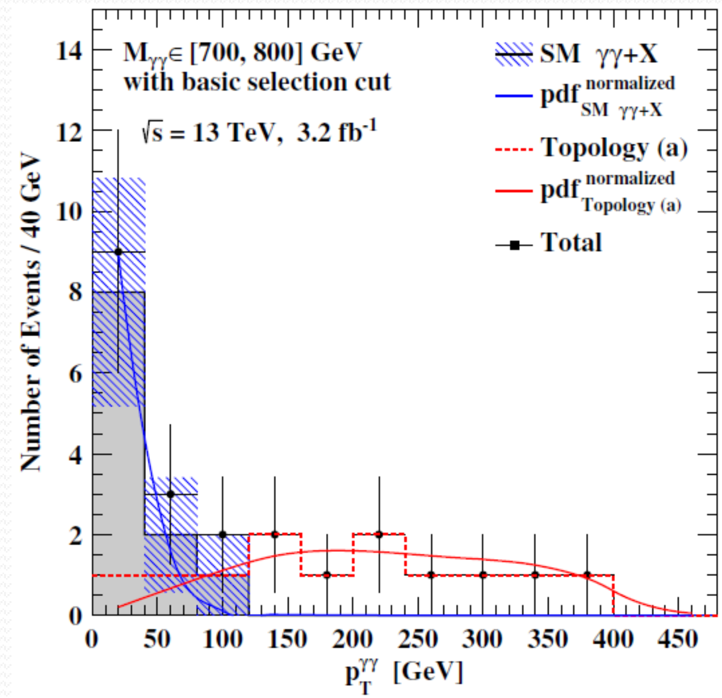
- ❑ Singly-produced primary mother particle is assumed.
- ❑ Antler topology: **small $p_T^{\gamma\gamma}$ is preferred** in the region of large diphoton invariant masses.

# Other Observables

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




[ATLAS at Moriond 2016]

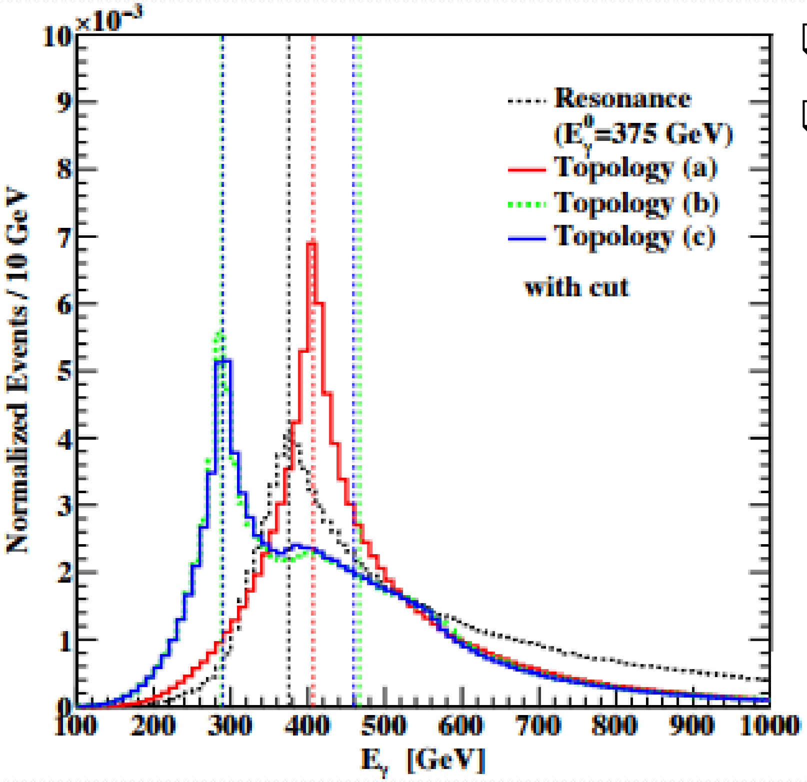



[Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

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

# Distinguishing Scenarios

## Example: energy spectrum



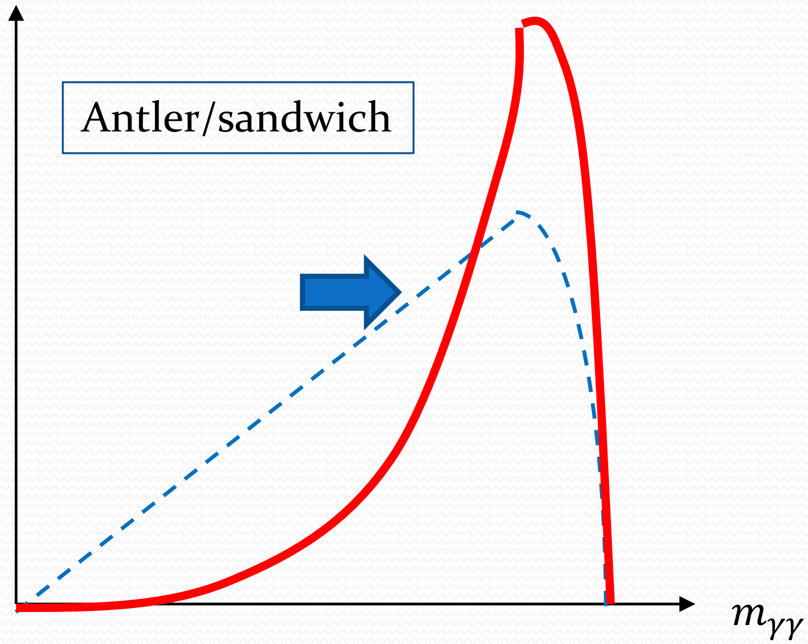

- ❑ High statistics assumed
- ❑ Distributions with basic cuts
  - ✓ Resonance: energy peak = half the $m_{\gamma\gamma}$ resonance peak
  - ✓ Antler (red): (in general) energy peak ≠ half the $m_{\gamma\gamma}$ resonance peak [Agashe, Franceschini and **DK**, arXiv:1209.0772]
  - ✓ Sandwich (green) and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

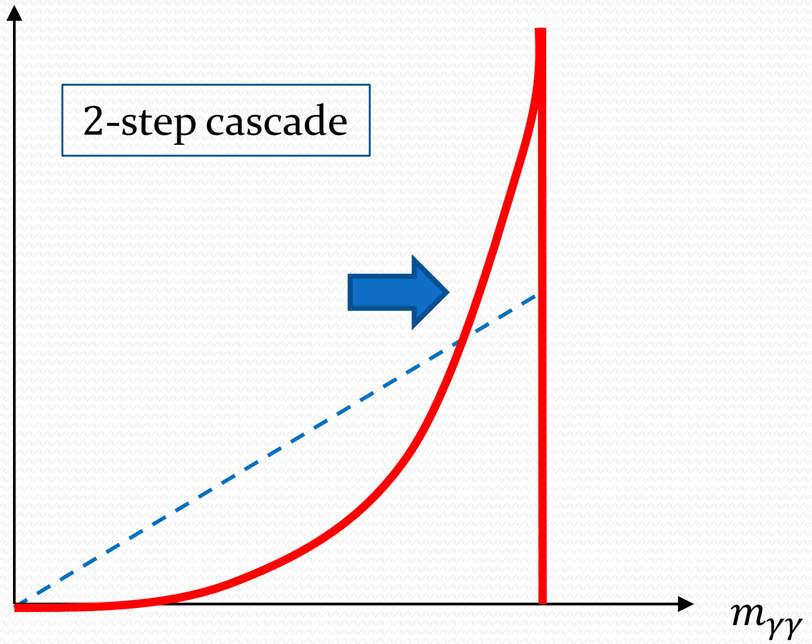
[Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

# Improvement with Spin Correlation

## 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!

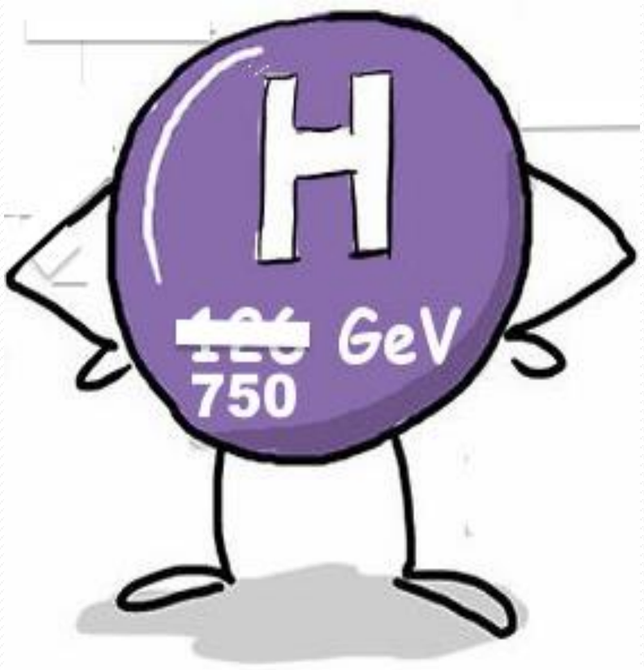


# Conclusions

## Summary

- ATLAS and CMS collaborations have reported an interesting resonance-like excess in the diphoton channel around 750 GeV.



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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.
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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**.
- Keep open-minded and enjoy the 750 GeV diphoton excess!

# Thank you!

# Back-up

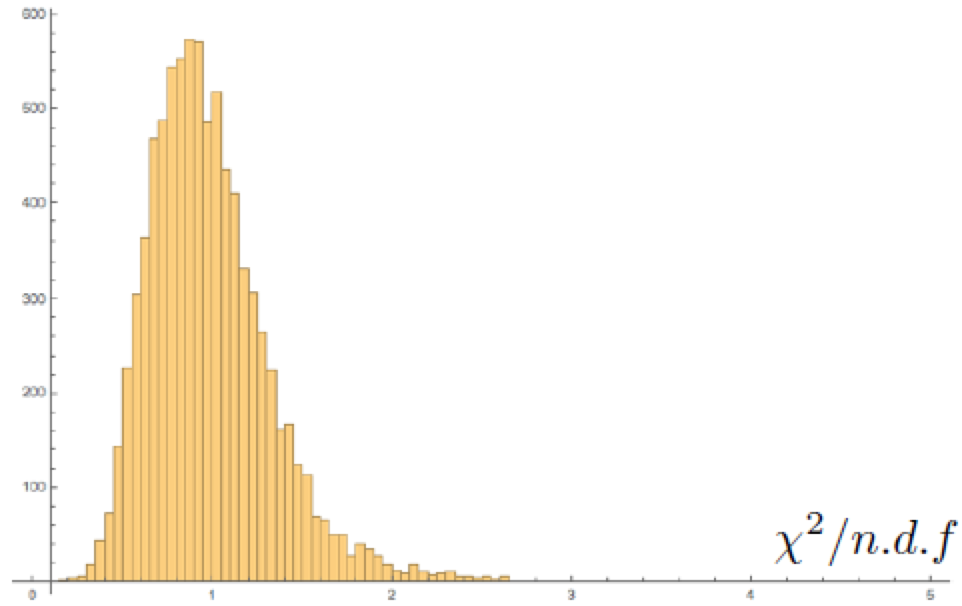
## Facts and issues

- 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 $\boldsymbol{ZZ}$ / $\boldsymbol{WW}$ / $\boldsymbol{Z\gamma}$ / $jj$ / $\ell\ell$ 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)

# Back-up

## Parameter & error estimates

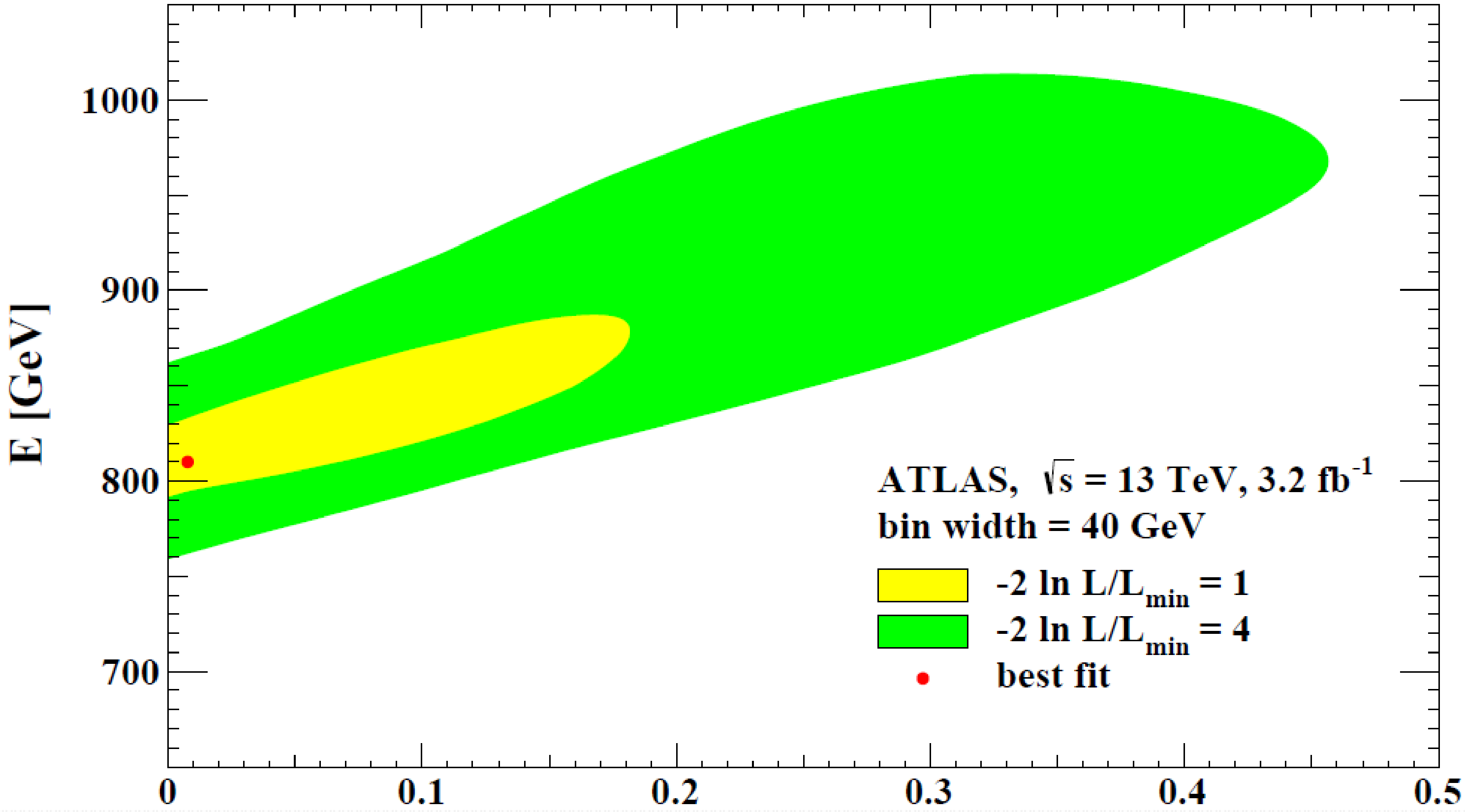
- Generating 10K pseudo data set
- via resampling of number-of-events (each bin), according to Poisson distribution with the mean value set to be the original data.
- Conducting the fit procedure for all pseudo data sets.
- Extracting mean values and $1\sigma$ confidence interval from the fitted parameter distributions.




- Given low statistics, our fit model (sig+bg) reproduces pseudo data samples well enough.

# Back-up

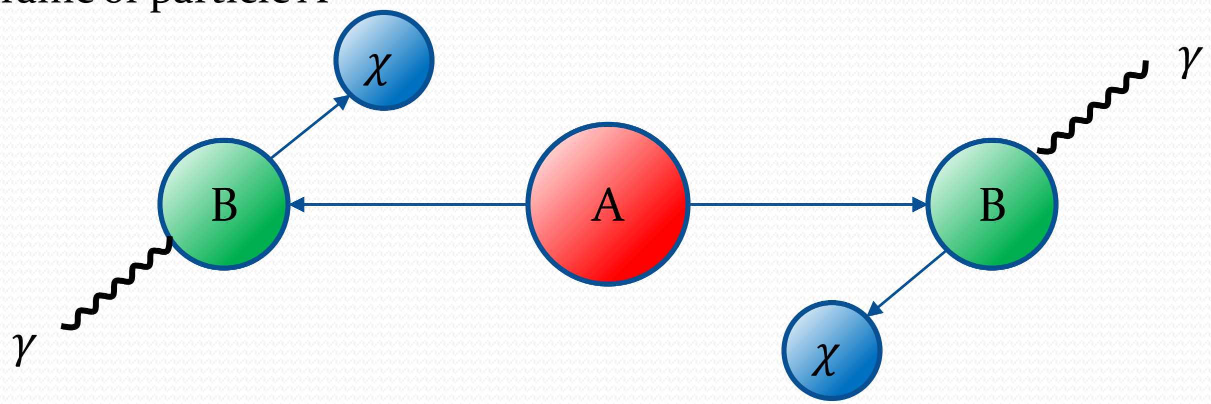
- Parameter & error estimates



# Back-up

## $p_T$ 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** .