Episode Diphoton 750 GeV:
A New Force Awakens

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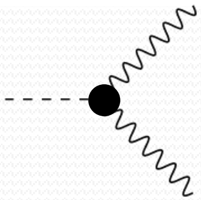
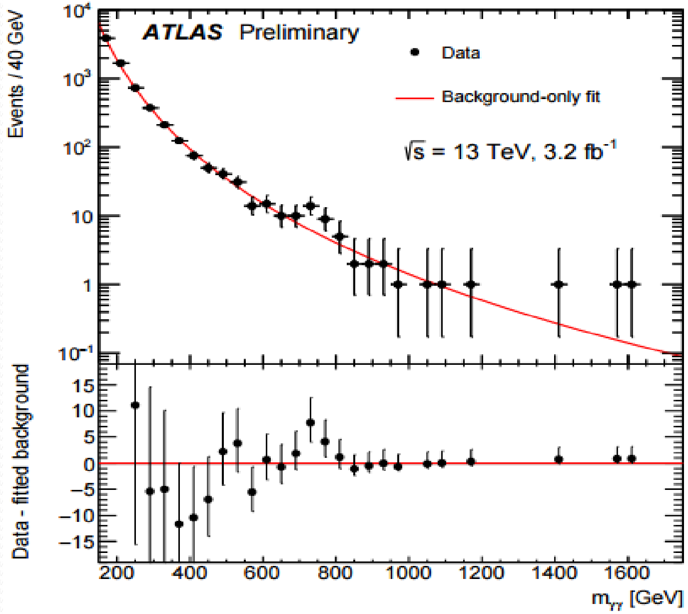
based on W.S. Cho, DK, K. Kong, S.H. Lim, K.T. Matchev, J.C. Park, M. Park
Phys. Rev. Lett. **116**, 151805 (2016) [arXiv:1512.06824]

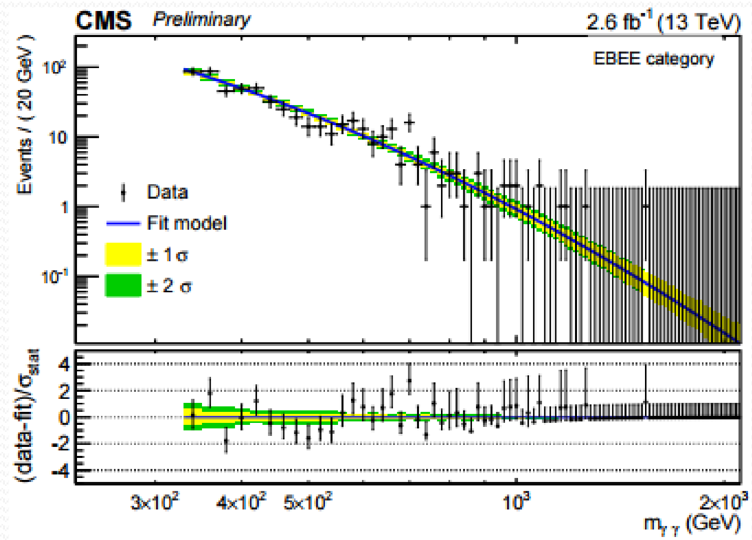
Phenomenon: A New Force Carrier?

Diphoton "resonance" search and excess



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



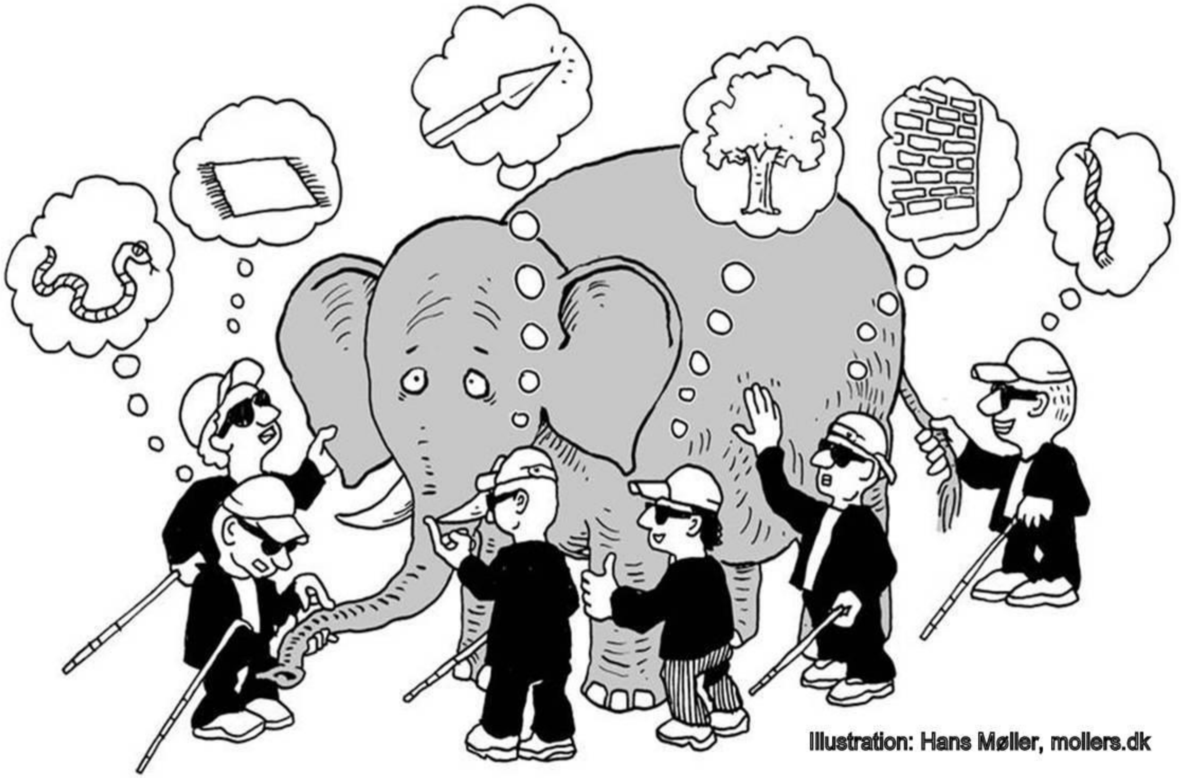


- Excess: $m_{\gamma\gamma}$~750 GeV, Γ~45 GeV
- Local (global) significance: $3.9\sigma (2.3\sigma)$
- Excess: $m_{\gamma\gamma}$~760 GeV, narrow Γ favored
- Local (global) significance: $2.6\sigma (2.0\sigma)$ → ~3.4σ local significance at Moriond

Phenomenon: A New Force Carrier?

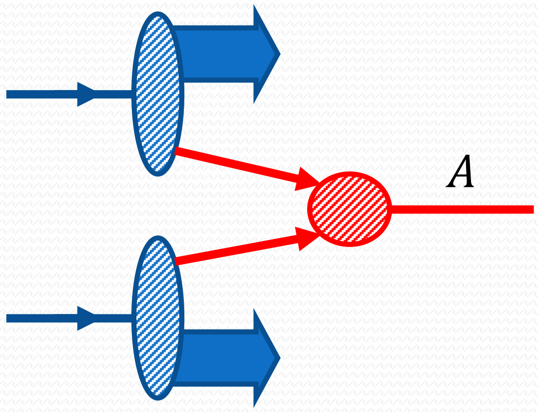
The blind men and an elephant

- **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



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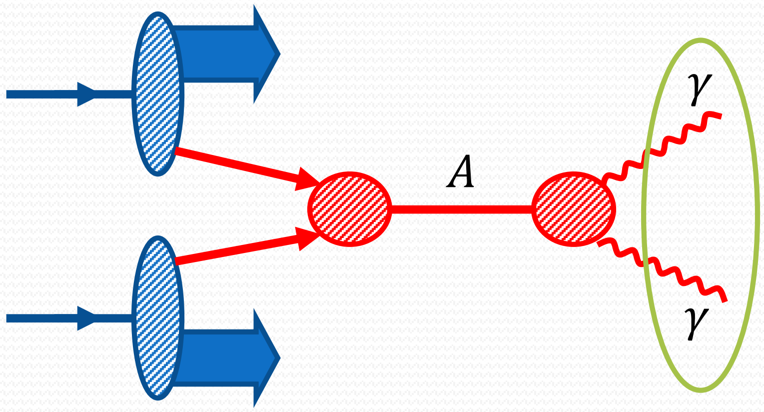

- $m_{\gamma\gamma} = m_A \approx 750$ GeV
- Simplest event topology, thus natural(?) interpretation
- **Spin 0** or spin 2 resonance (interpreted as a **new force carrier**) with EFT, 2HDM, SUSY, Extra-Dim, Compositeness, …

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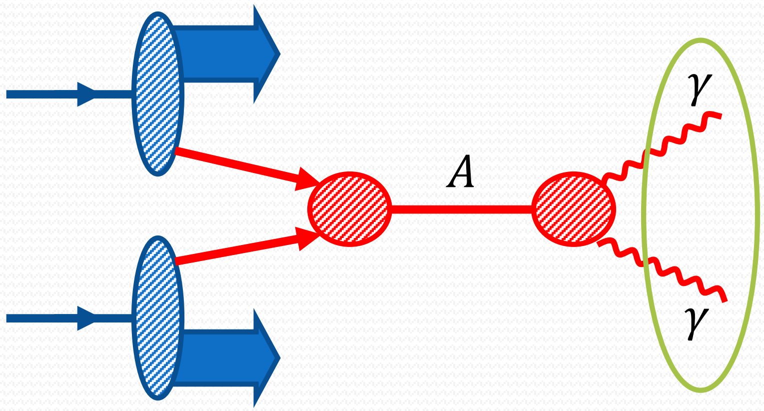

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- Tension?: (rather) **large decay width** – 6% of the particle mass [ATLAS-CONF-2015-081]
  - ✓ cf. Z boson – 2.7%, W boson – 2.6%, t quark – 1.1%, h boson – 0.3% (<2.7%)
  - ✓ No other decay modes have been observed.

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.

Large Decay Width Is an Intrinsic Property?

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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?

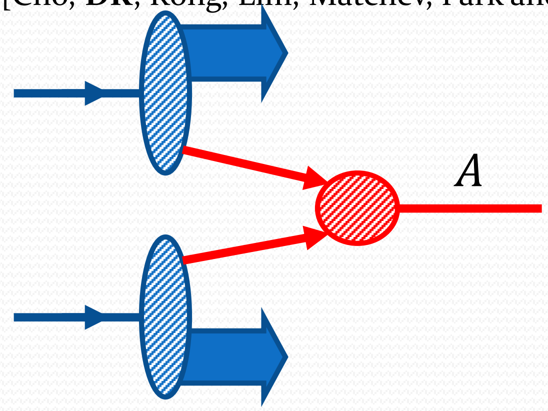
I answered

- 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 approach**

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



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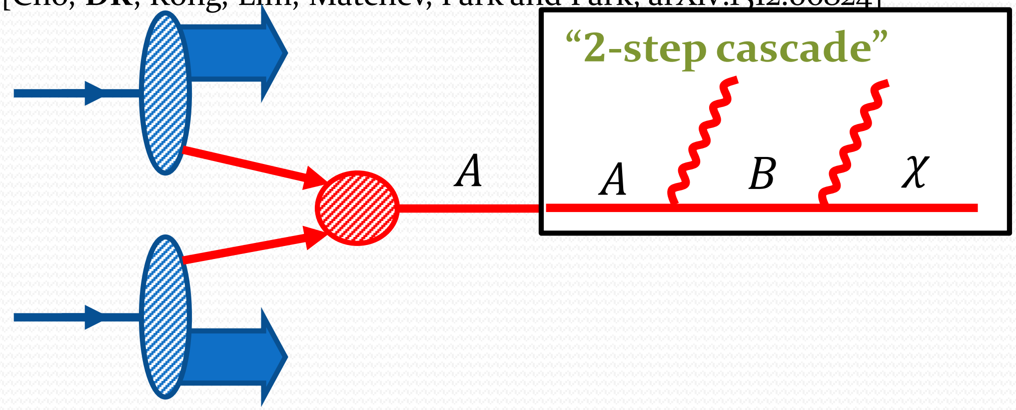

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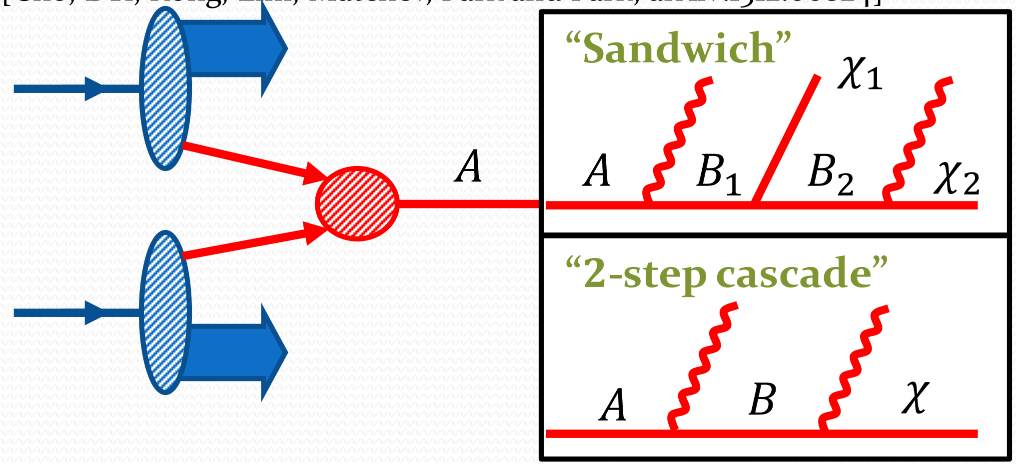

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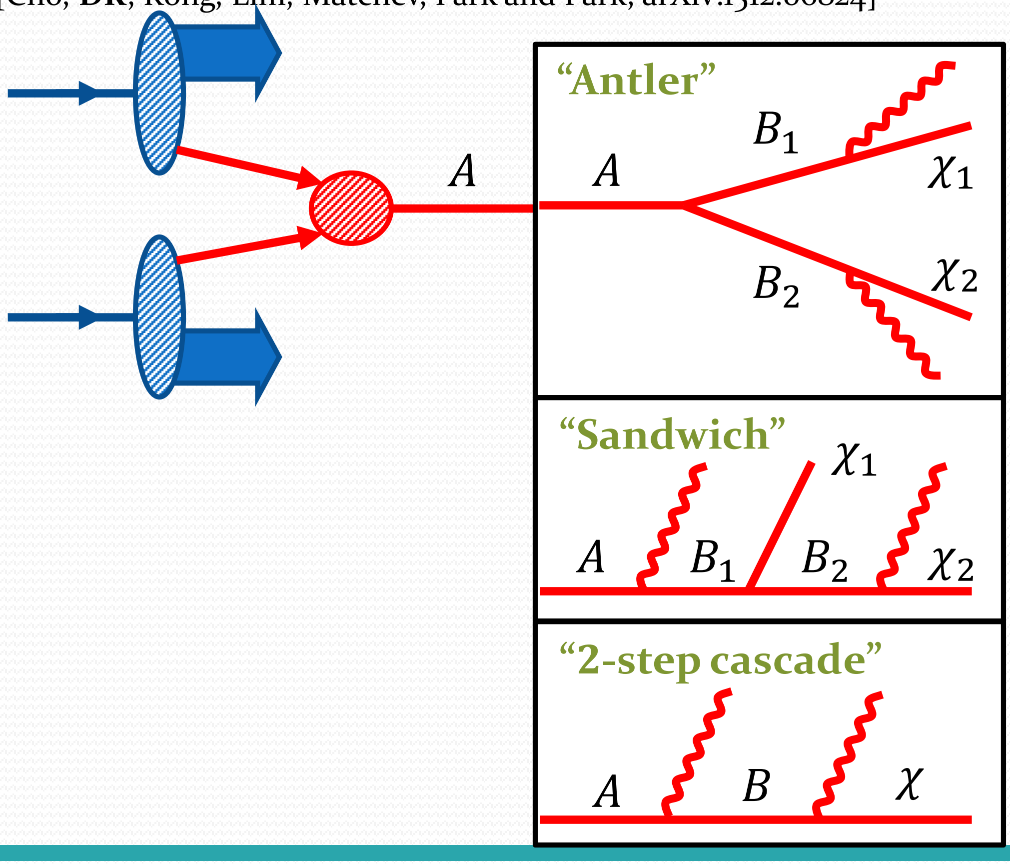

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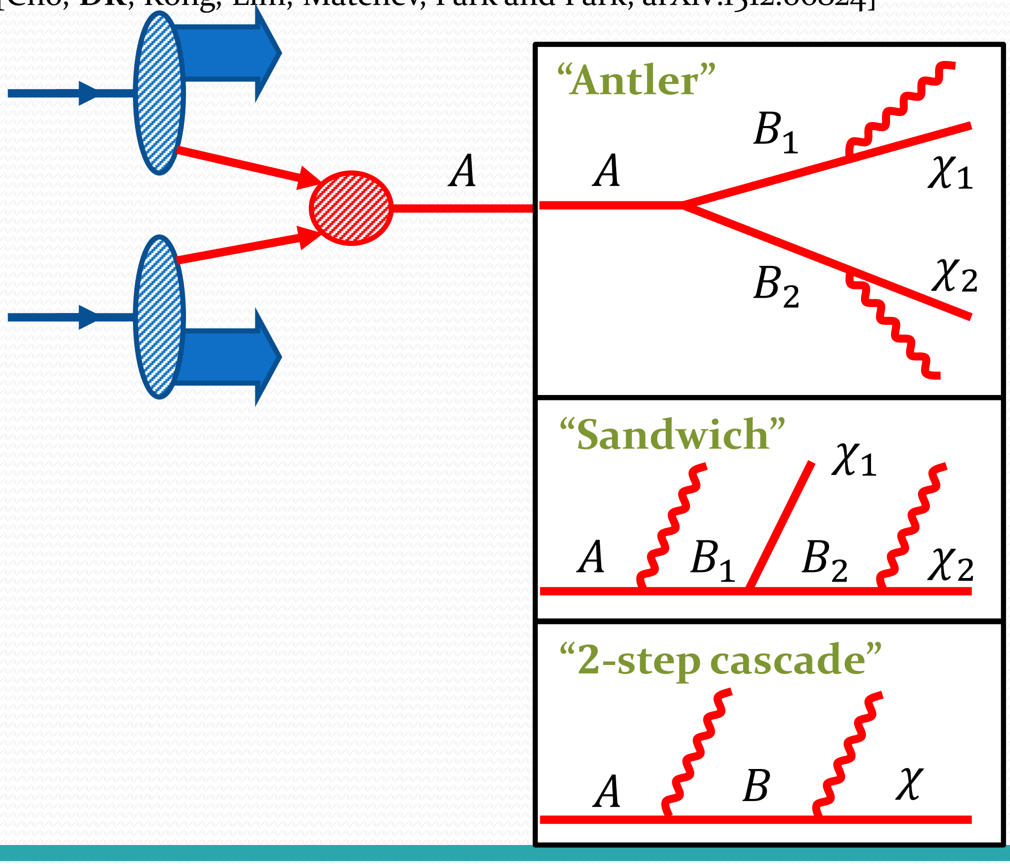

- ❑ Diphoton invariant mass distributions coming from
  - ✓ a **heavier** (than 750 GeV) **resonance** and
  - ✓ its **non-minimal decays** into the **two photons plus (visible or invisible) χ’s**

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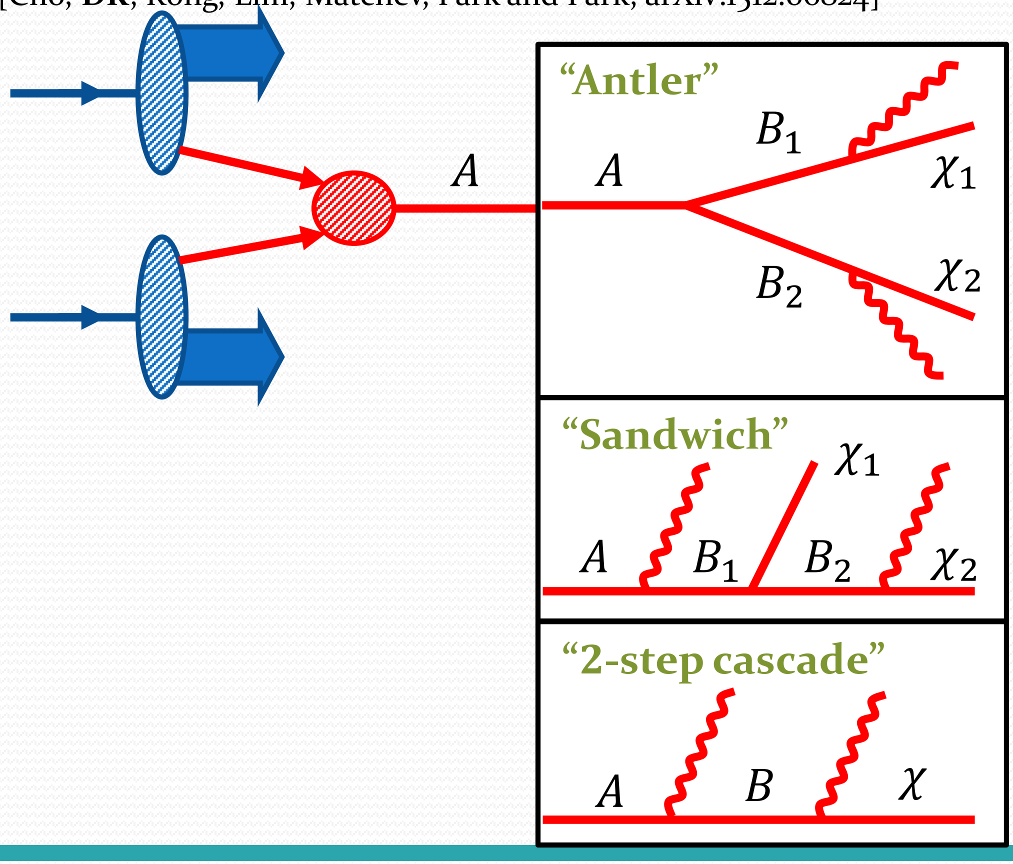


- ❑ Diphoton invariant mass distributions coming from
  - ✓ a **heavier** (than 750 GeV) **resonance** and
  - ✓ its **non-minimal decays** into the **two photons plus (visible or invisible) χ’s**
- ❑ Obviously, **more new particles** not in loops, (which could be matter particles), are predicted!

Non-minimal Decay Scenarios

Why those three topologies?

- Study of decay topologies of 2 visibles (here γ) with # of invisibles (or less clean visibles) ≤ 2
- Shapes of invariant mass distributions of v_1, v_2

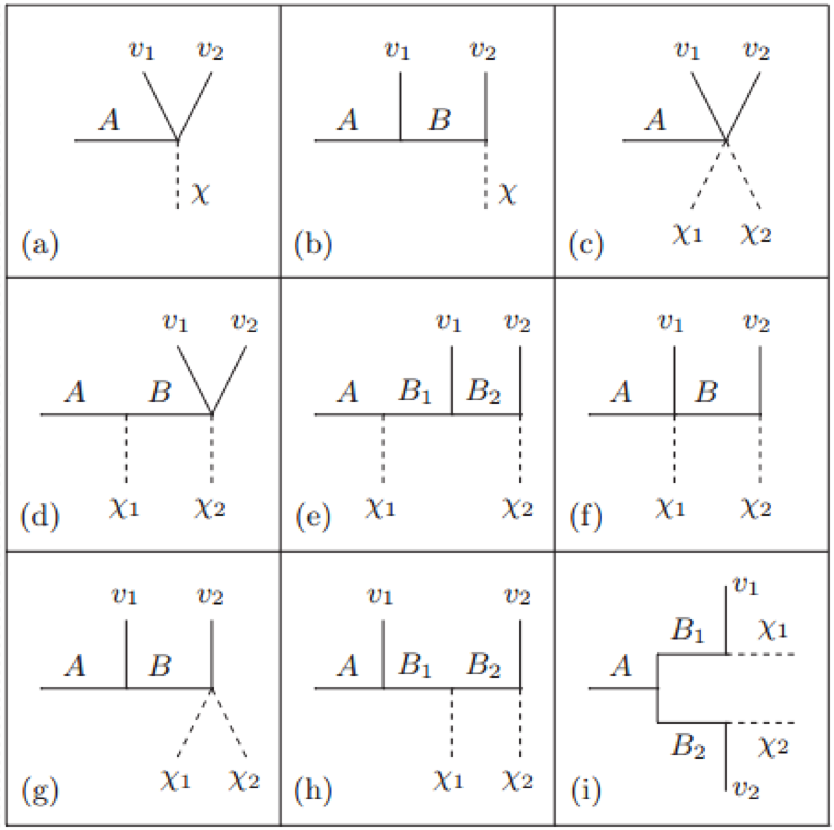
$$\frac{dN}{dm} \equiv f(m;\ M_A, M_{B_i}, M_{\chi_j})$$

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

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

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

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

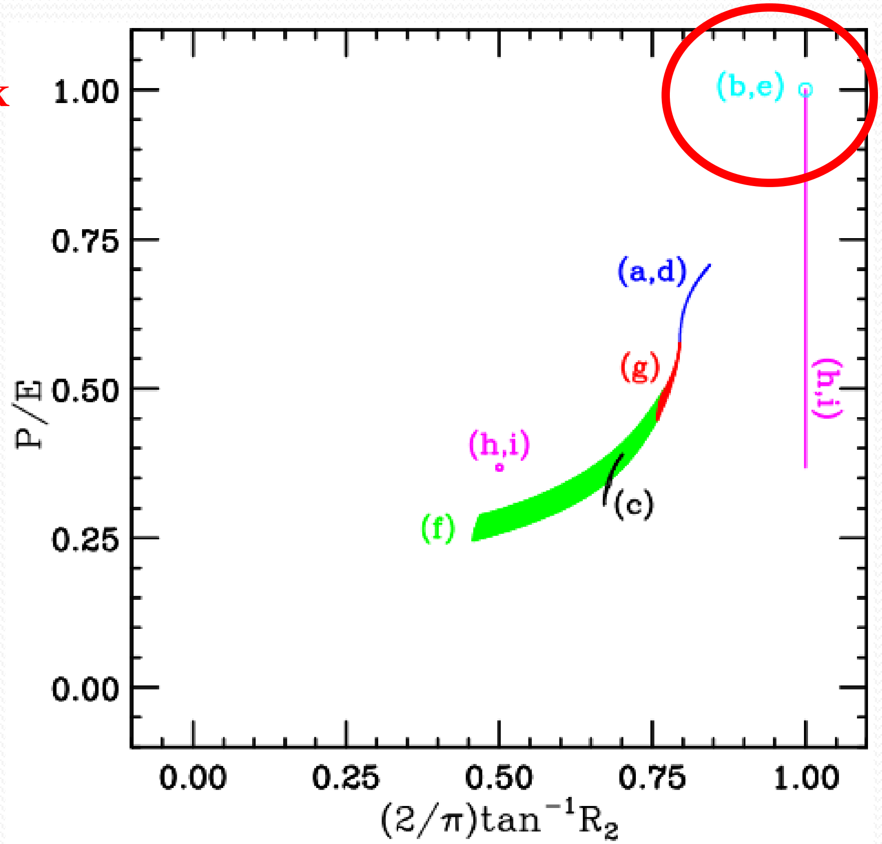


[Cho, **DK**, Matchev and Park, PRL (2014), arXiv:1206.1546]

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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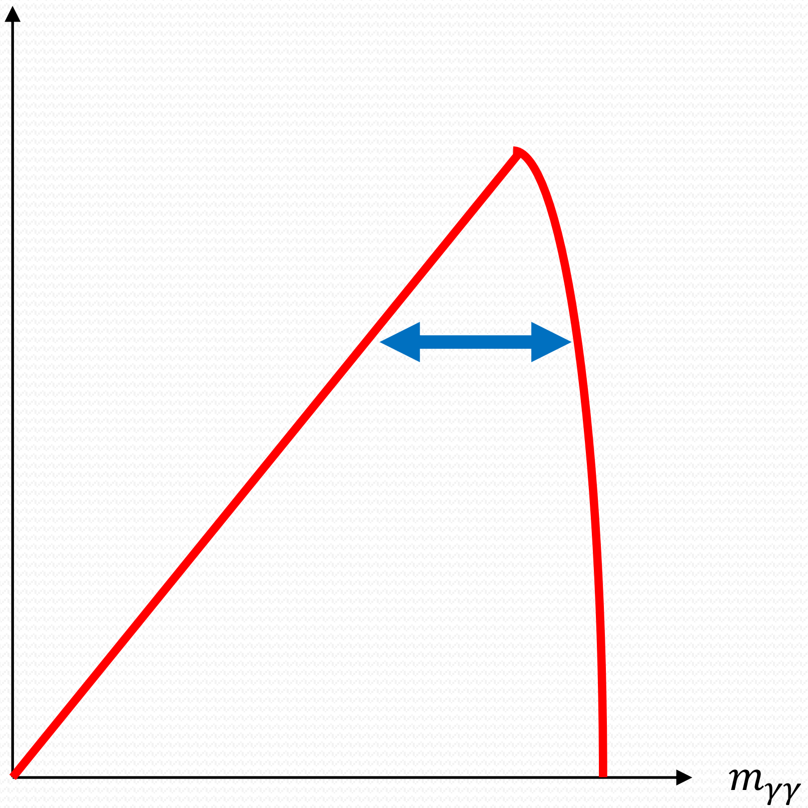
Common Features

Advantages

- A **broad width** naturally arises.



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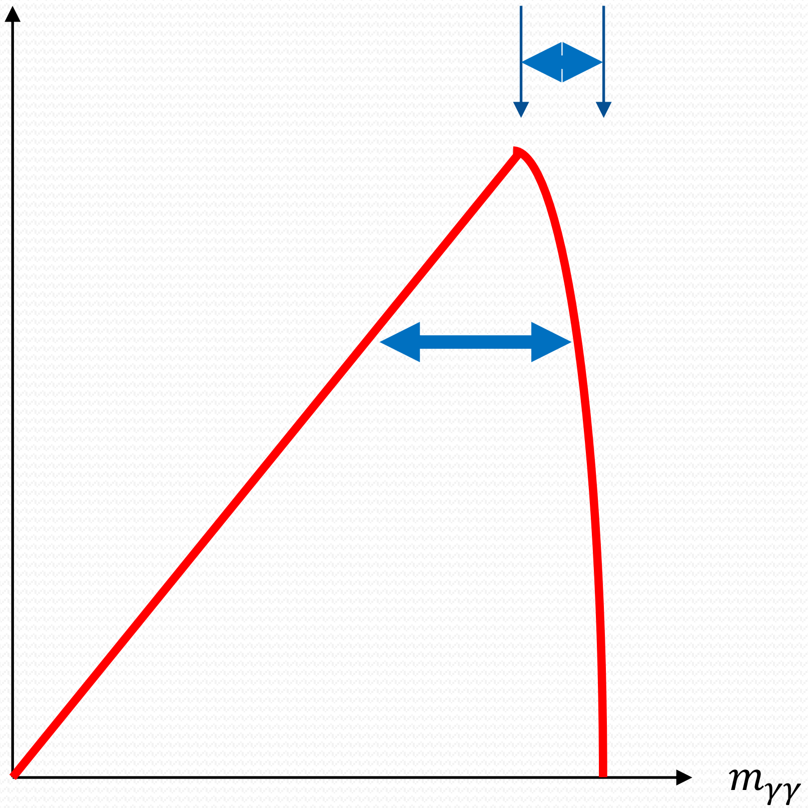

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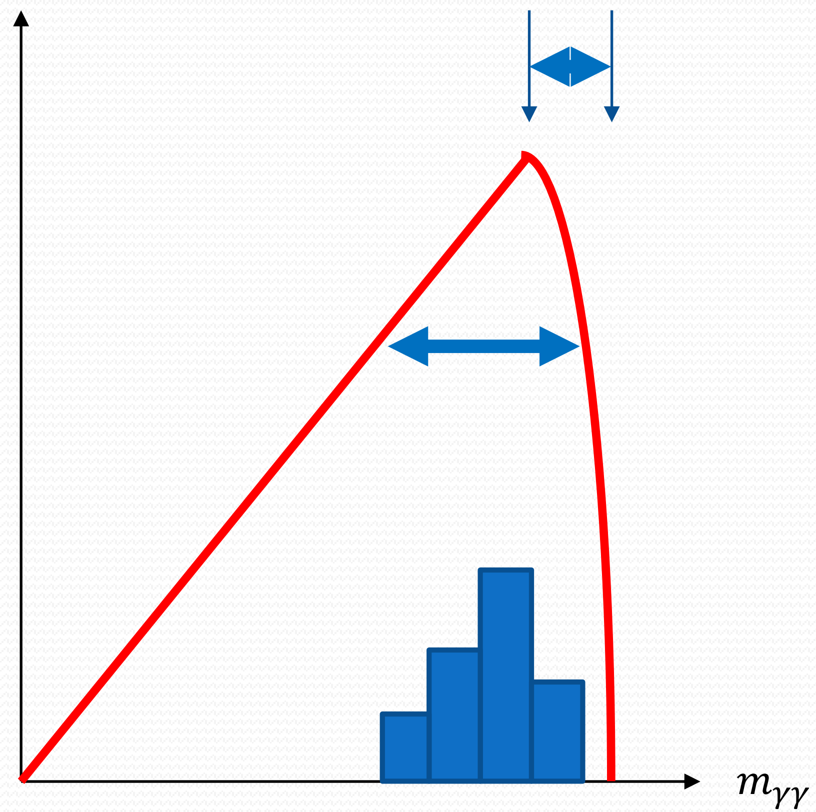
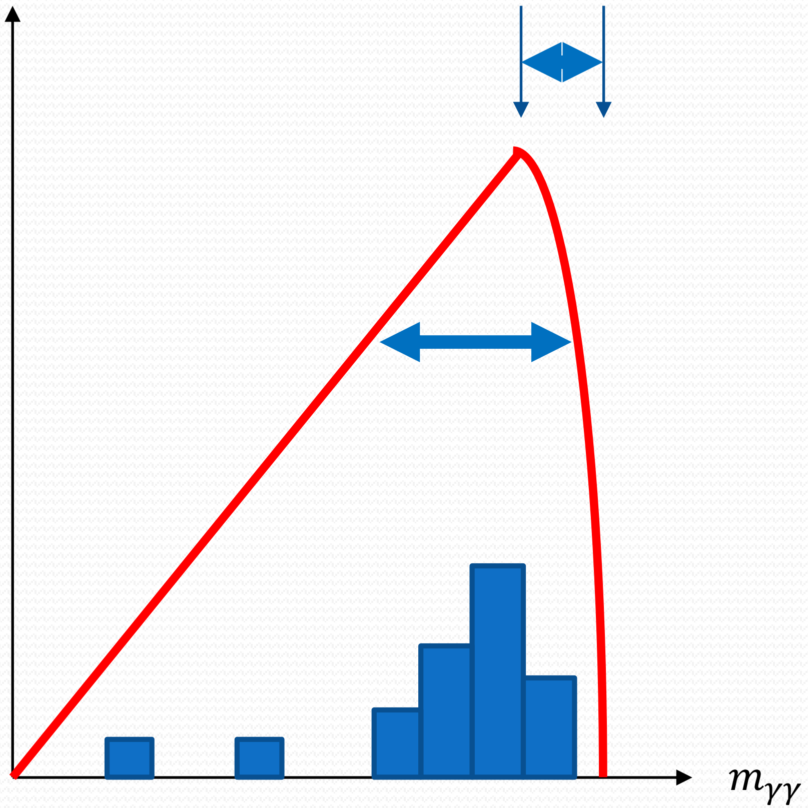


Common Features

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.



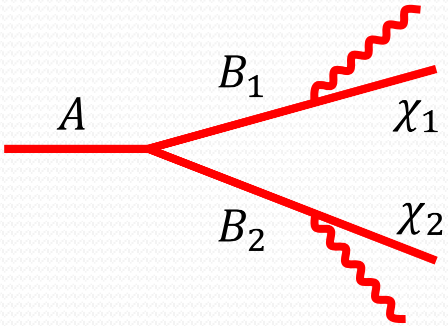
Individual Features

Antler topology

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

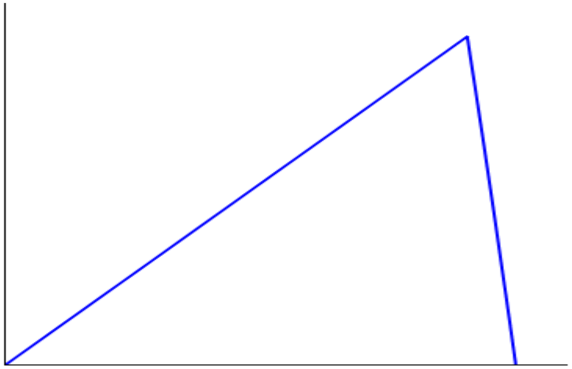
$$f(m) \sim \begin{cases} \eta\, m\,, & 0 \le m \le e^{-\eta} E, \\ m \ln(E/m)\,, & e^{-\eta} E \le m \le E, \end{cases}$$

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



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

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



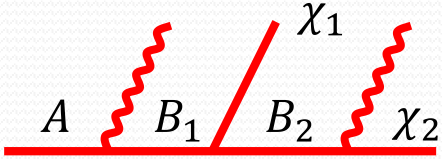
Individual Features

Sandwich topology

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

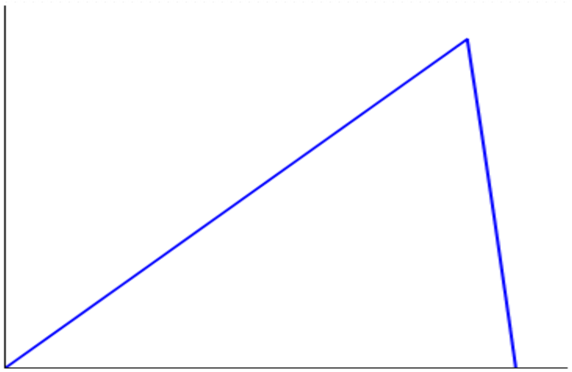
$$f(m) \sim \begin{cases} \eta\, m\,, & 0 \le m \le e^{-\eta} E, \\ m \ln(E/m)\,, & e^{-\eta} E \le m \le E, \end{cases}$$

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



- $f(m)$ is identical to that of the antler, but with different definitions of E and η.
- In our benchmark study, $(A, B_1, B_2, \chi_i) =$ (U(1) Vector boson, Scalar, Fermion, Fermion)

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



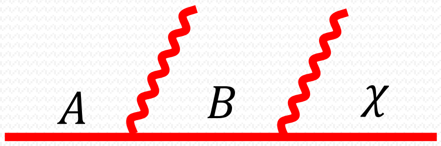
Individual Features

2-step cascade topology

- 2-step cascade topology

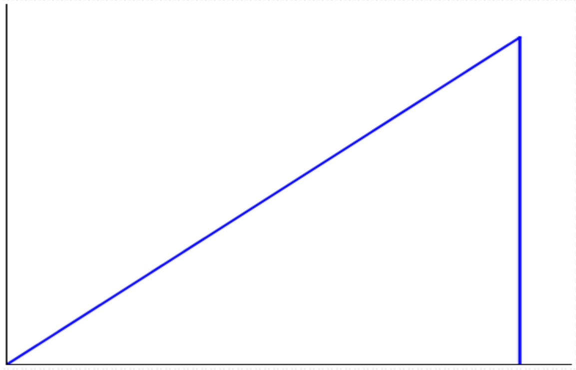
$$f(m) \sim m,$$

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



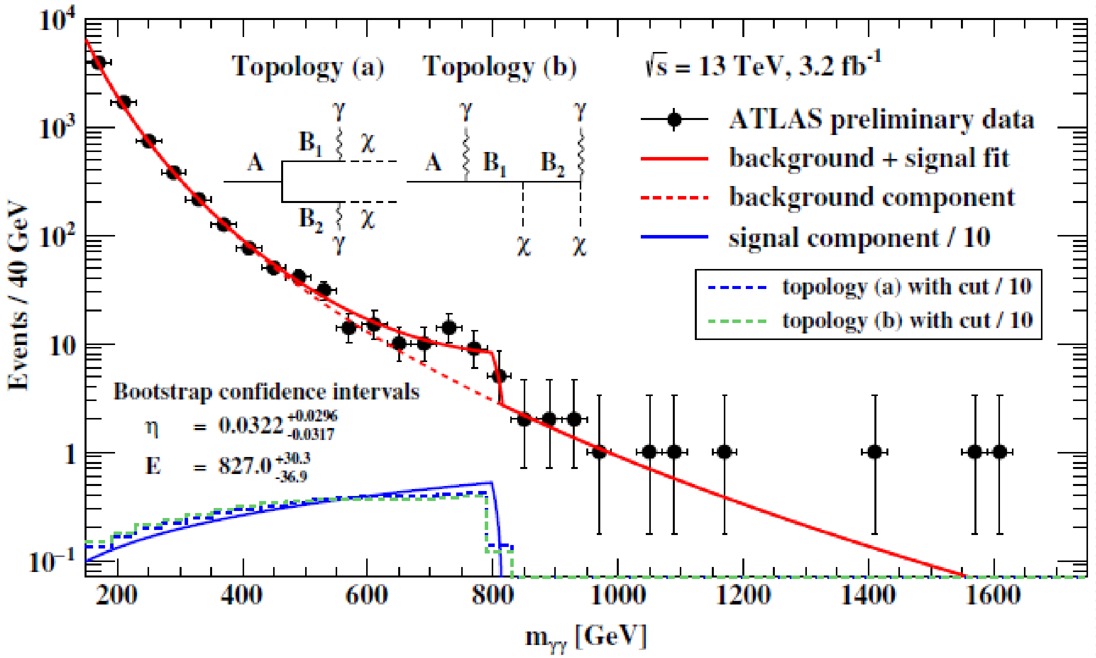
- Famous triangular shape
- Only a **single parameter, *E*, determines the shape**.
- In our benchmark study, $(A, B, \chi) =$ (U(1) Vector boson, Scalar, U(1) Vector boson)

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



Data Analysis

Fit result: antler/sandwich

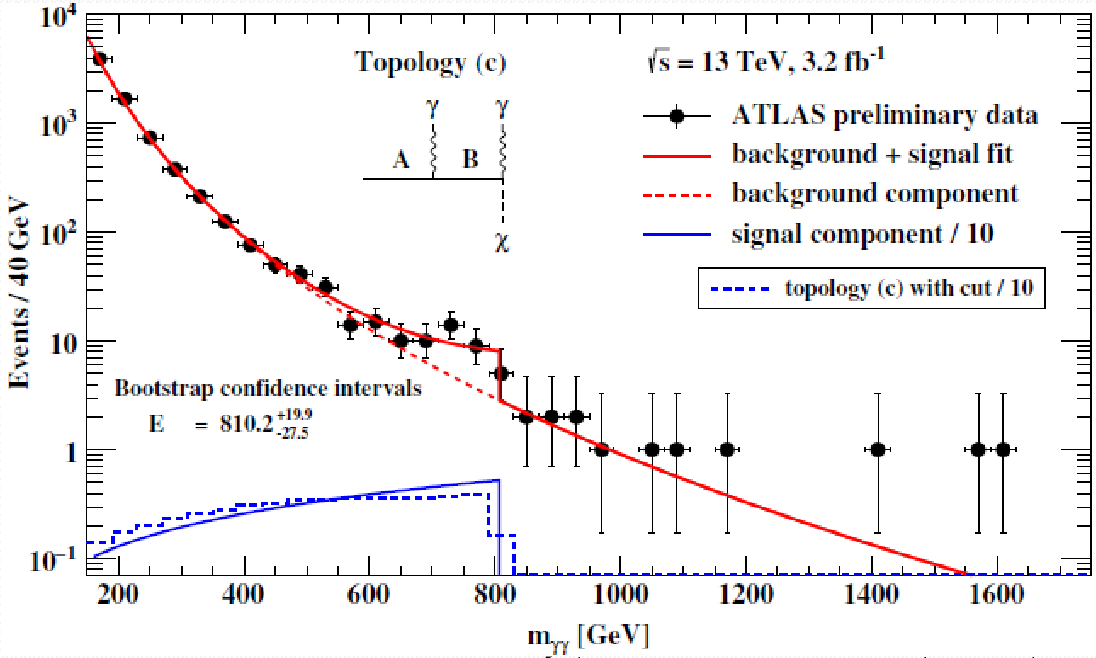


[Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

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

Data Analysis

Fit result: 2-step cascade



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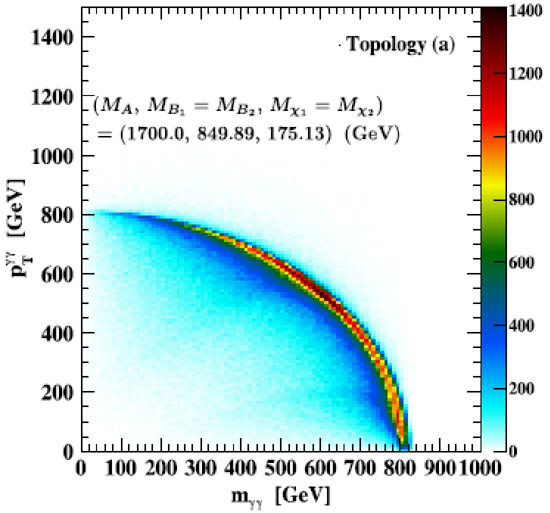
- Same fit scheme as before
- Best-fit values: $\boldsymbol{E = 810^{+20}_{-28}}$ **GeV** $[\chi^2 = 0.69]$

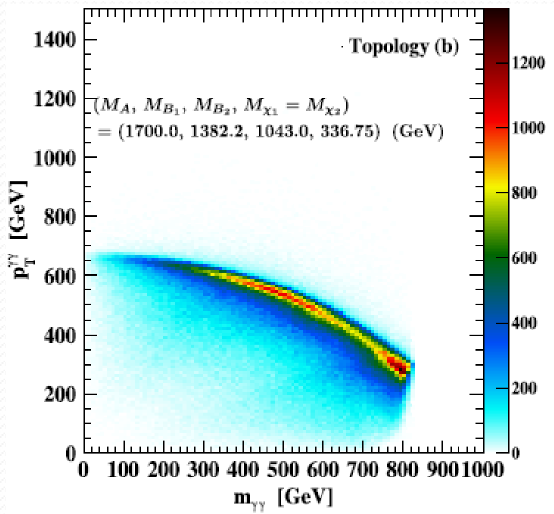
Other Observables

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

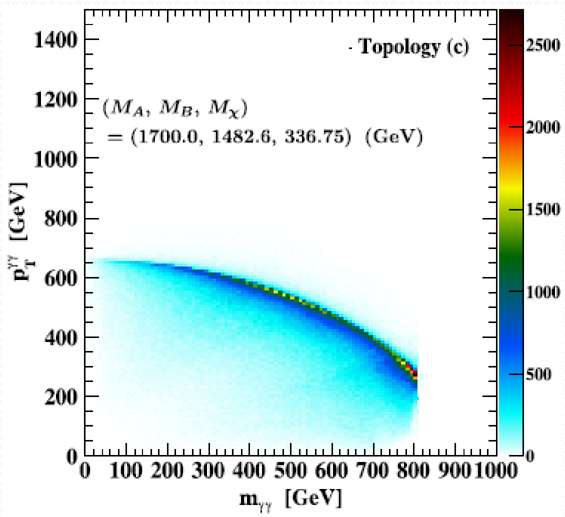
Antler



Sandwich



2-step cascade



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- Singly-produced primary mother particle is assumed.

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

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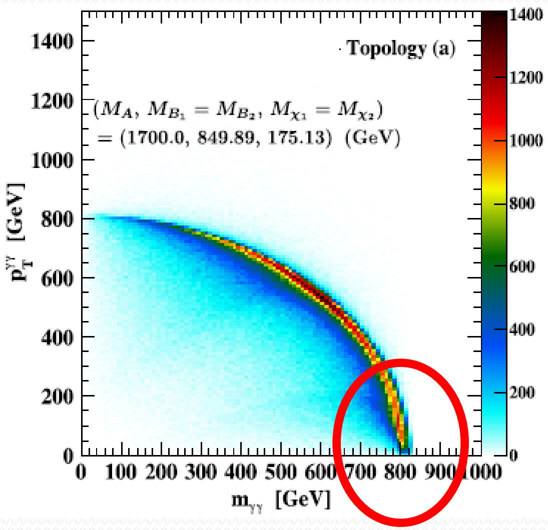

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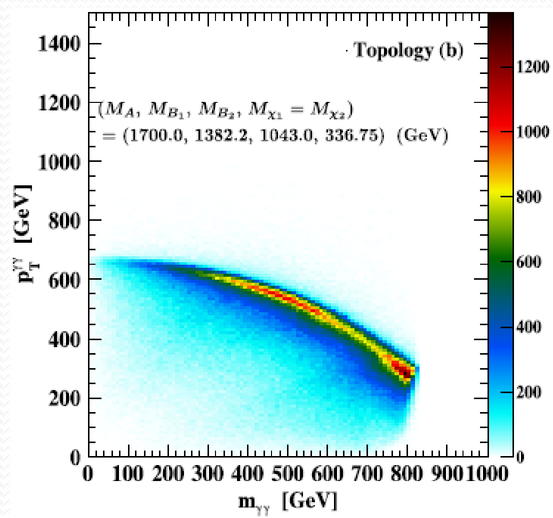

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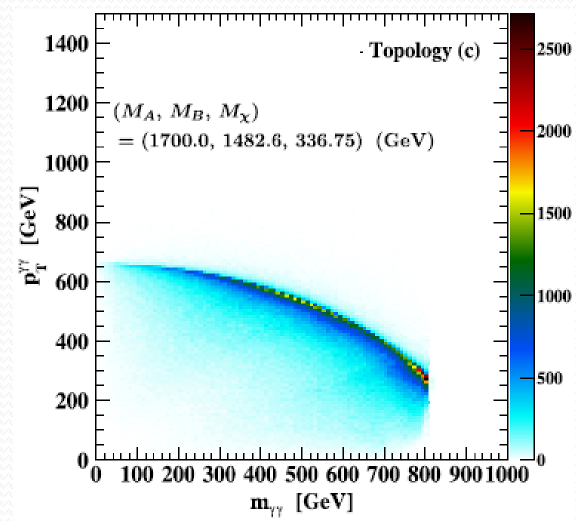

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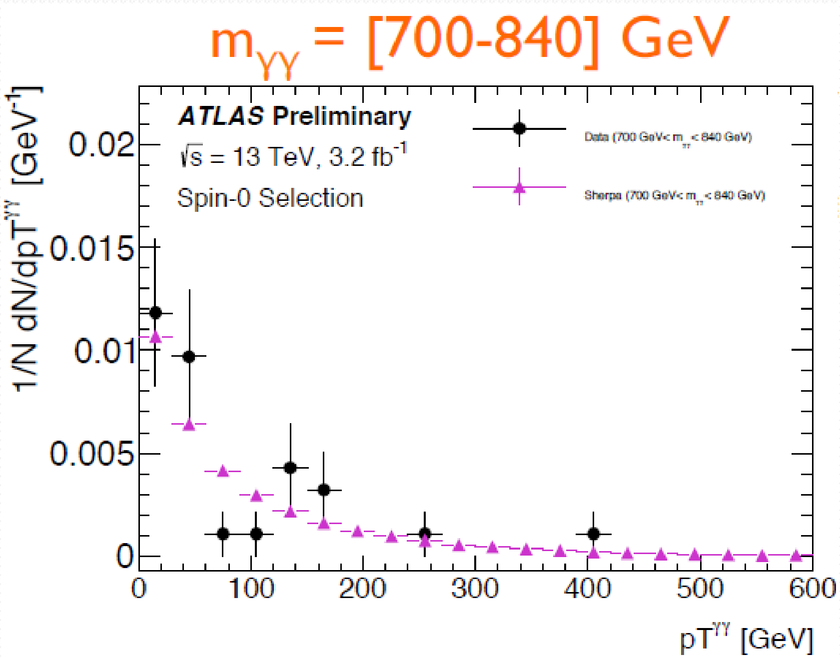
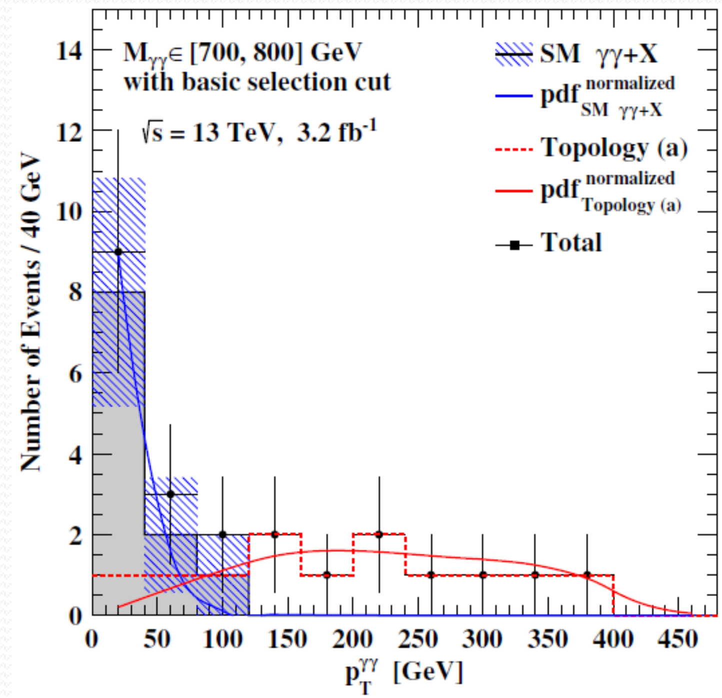
- ❑ Singly-produced primary mother particle is assumed.
- ❑ Antler topology: **small $p_T^{\gamma\gamma}$ is preferred** in the region of large diphoton invariant masses.

Other Observables

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



[ATLAS at Moriond 2016]



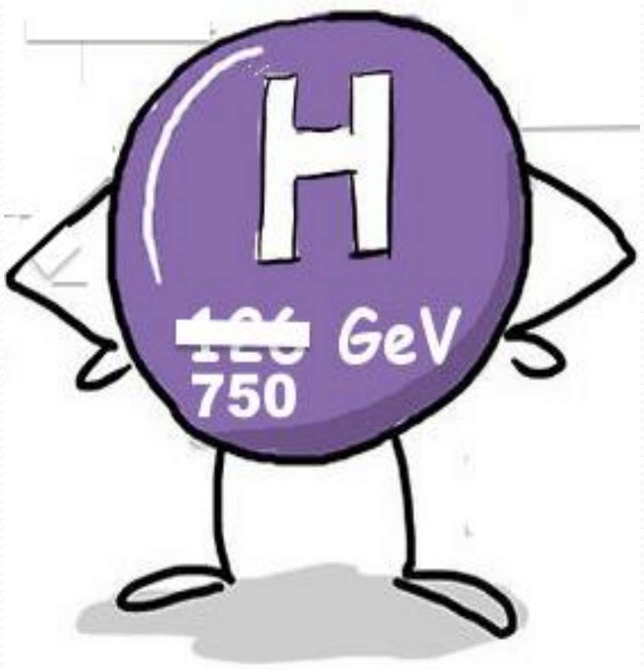
[Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

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

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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- 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!

Back-up

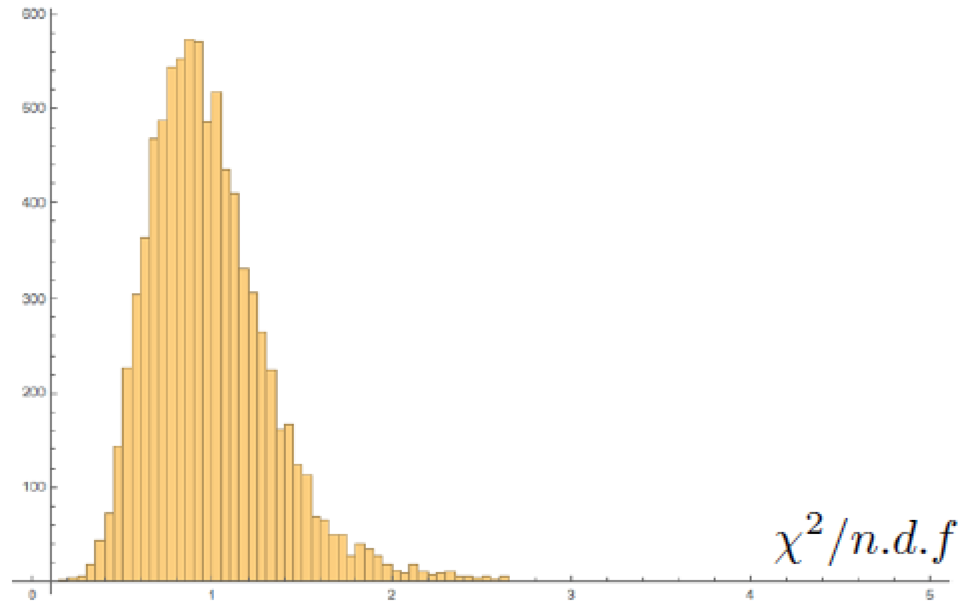
Facts and issues

- 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: $\mathcal{O}(1)$ 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 1σ confidence interval from the fitted parameter distributions.



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

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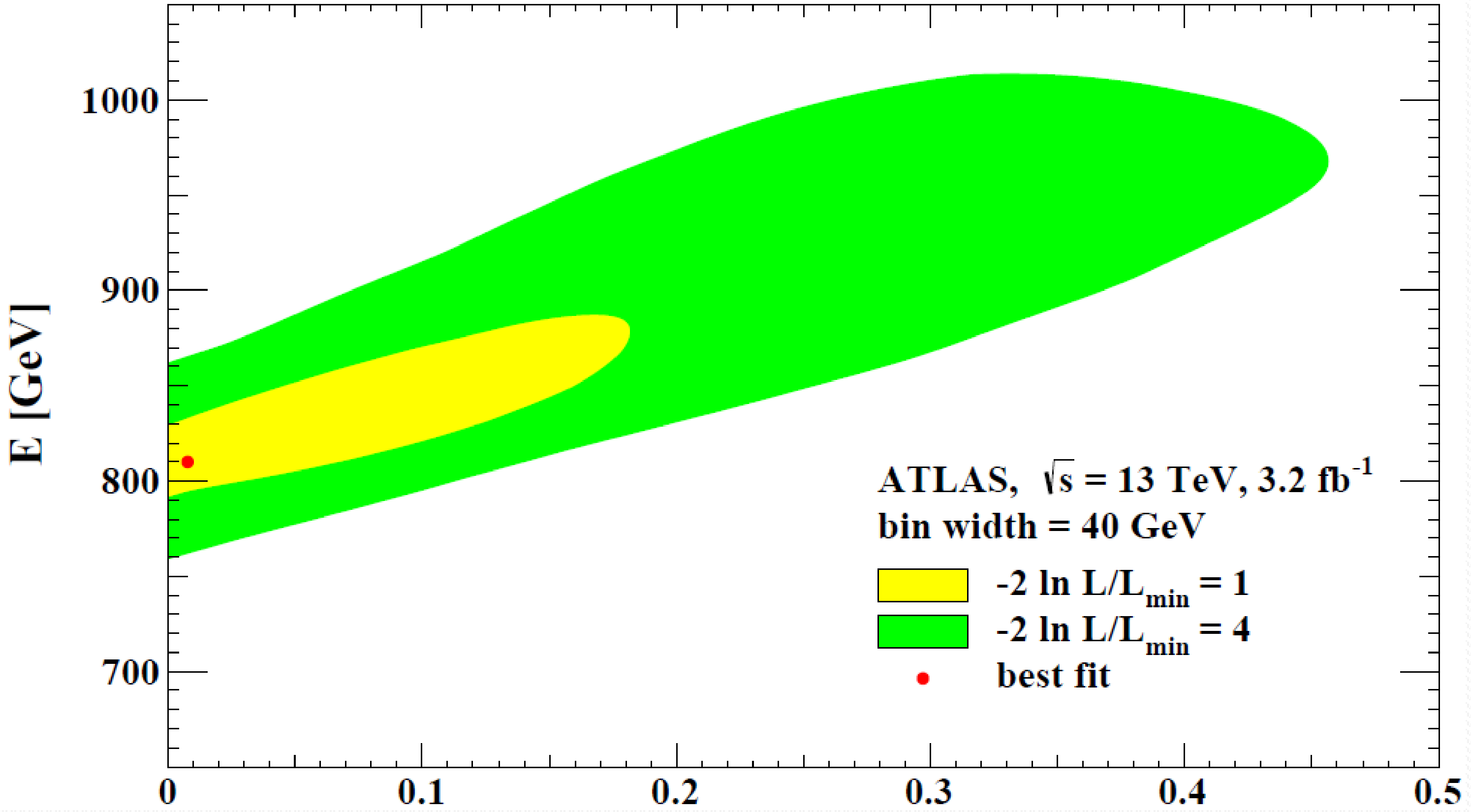
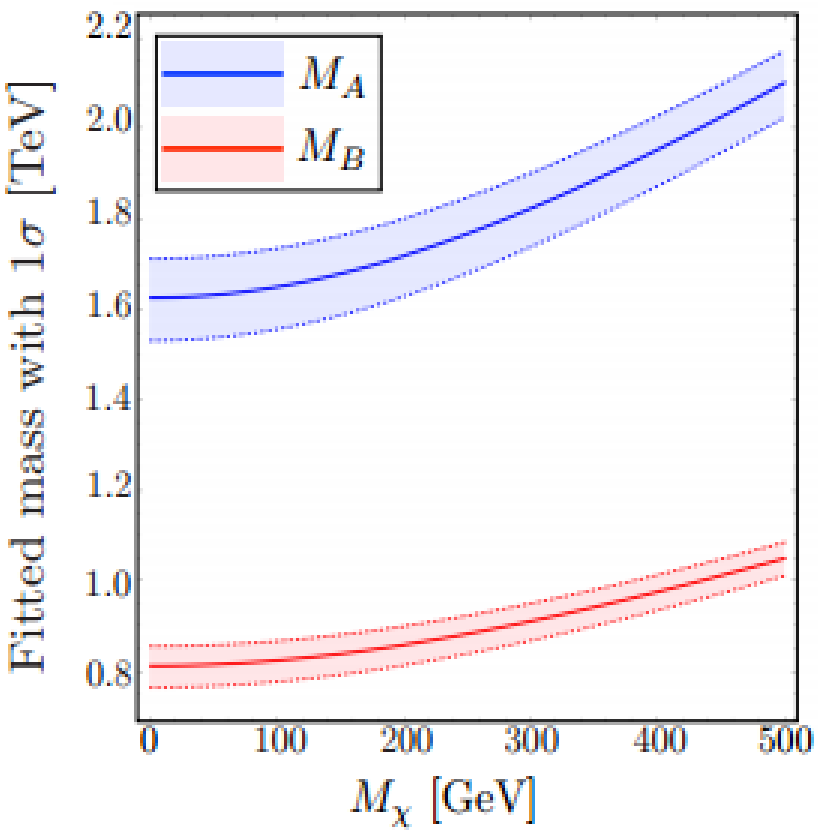
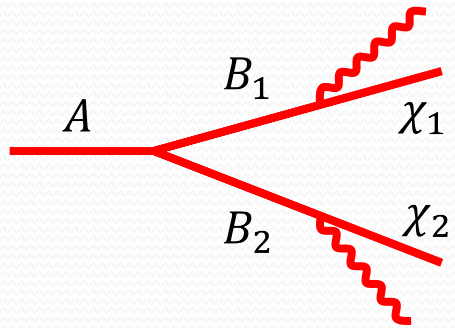
- Parameter & error estimates



Back-up

Mass projection: antler topology



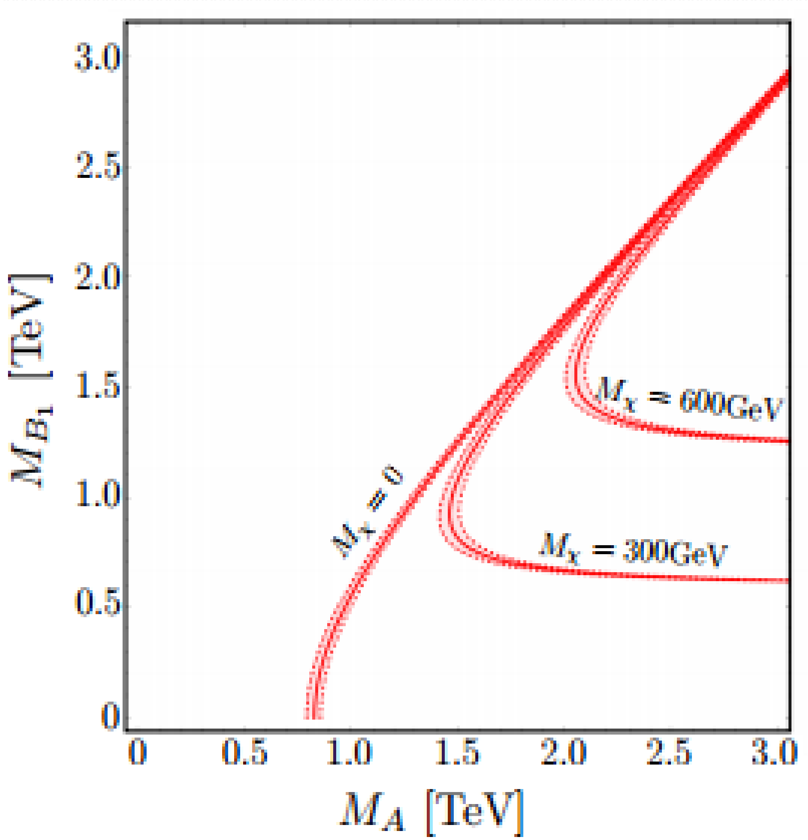


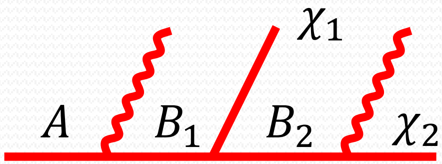
- Symmetric antler assumed, i.e., $B_1 = B_2$, $\chi_1 = \chi_2$

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

Back-up

Mass projection: sandwich topology



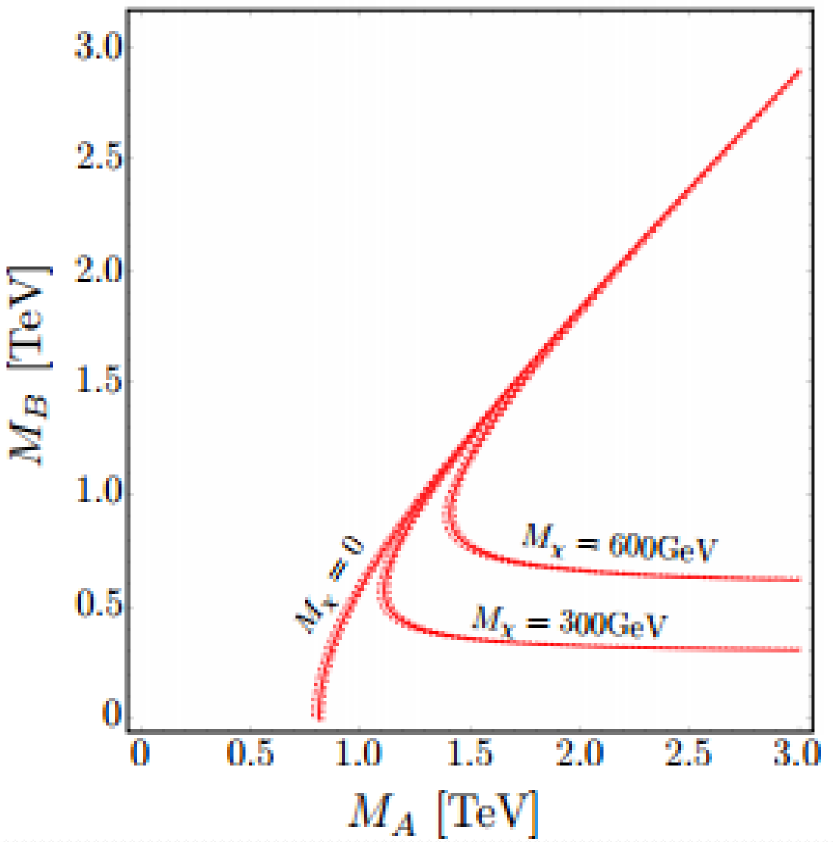


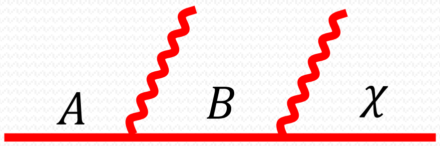
- Same invisible particles assumed, i.e., $\chi_1 = \chi_2$

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

Back-up

- **Mass projection: 2-step cascade topology**



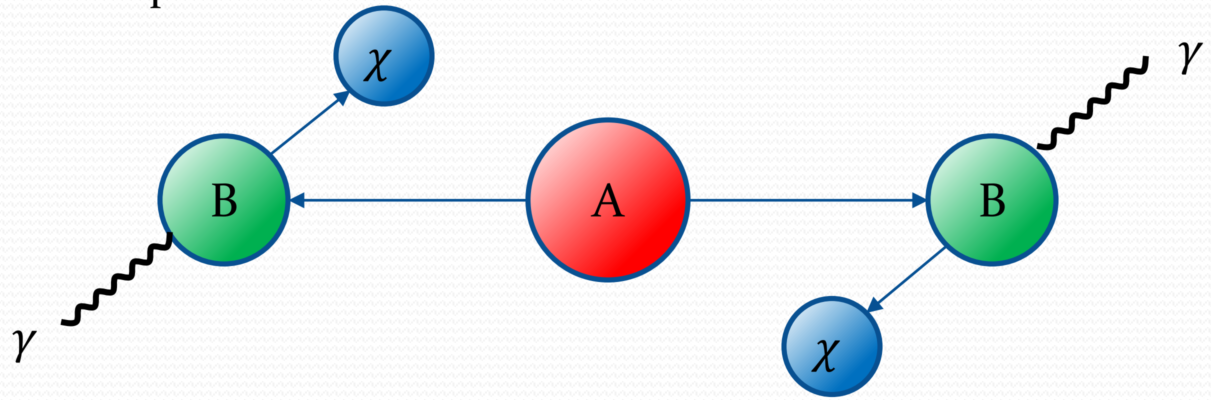


[Cho, **DK**, Kong, Lim, Matchev, Park and Park, arXiv:1512.06824]

Back-up

p_T vs. invariant mass: antler topology

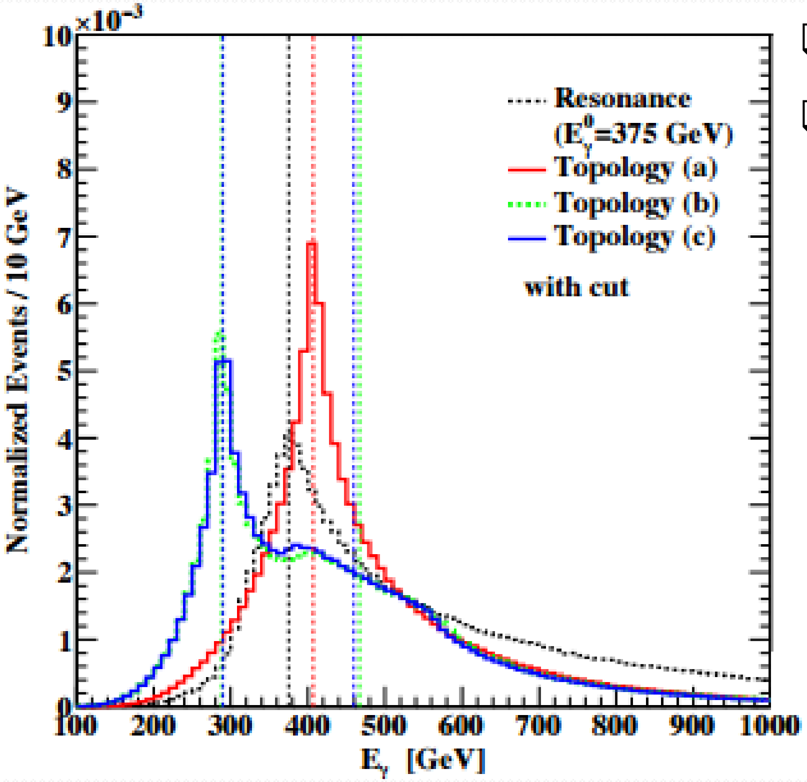
- In the rest frame of particle A



- ✓ 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 χ are emitted back-to-back.
- ✓ For the events having the maximum invariant mass, the two χ's are likely to be back-to-back, i.e., **no significant transverse momentum of two χ's** .

Back-up

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]

Back-up

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!