Faking The Diphoton Signal by Displaced Dark Photon Decays

Yuhsin Tsai

1603.00024 YT, Liantao Wang, Yue Zhao

Light Dark World, July 14 2016
Collider Signals from a Dark Sector
Missing energy, displaced decays

$p \rightarrow j, \gamma, \ldots$ (MET)

$p \rightarrow 2j, 2\ell^\pm, \ldots$

hidden valley, twin hadrons,…
In this talk: BSM signals fake SM objects

\[ p \rightarrow \text{looks like} \rightarrow j, \gamma, \ldots \]
Why complicating things?

There are good motivations to think about the FAKE signals

The inconsistency between one searching result to the others may come from the mis-identification of FAKE particles

When studying exotic collider objects (like displaced decays), the detector may seem an exotic signal to be "normal"
In this talk: BSM signals fake SM photon
Require $f \sim < 10$ GeV for the decay to be inside detector. This is challenging for an electrically charged mediator.
In this talk: BSM signals fake SM photon

fake both converted/unconverted photons, easier to realize

\[ \epsilon \sim 10^{-4}, \quad m_{\gamma'} = \mathcal{O}(100) \text{ MeV} \]

\[ c\tau_{\text{lab}} > 1 \text{ cm} \]

See also Agrawal et al. (15’), Dasgupta et al. (16’).
Dark Photon Fakes A SM Photon
Tight photon identification at ATLAS
Photon-id at ATLAS: before ECAL
Photon-id at ATLAS: before ECAL
Photon-id at ATLAS: $r < 34 \text{ mm}$

No hit at the 1st layer of Pixel detector
Photon-id at ATLAS: $34 < r < 400 \text{ mm}$

If converted, needs to leave $> 3$ space points at Pixel or SCT

There can be either 1 or 2 tracks
If $< 3$ hits before TRT: identified as an unconverted photon

Photon-id at ATLAS: $400 < r < 1500$ mm
Photon-id at ATLAS: **in TRT** (Transition Radiation Tracker)

Converted photon can in principle be identified in the TRT but with a much worse resolution

=> need well-separated e+e- tracks, difficult for a high pT photon
Photon-id at ATLAS: in TRT (Transition Radiation Tracker)

Converted photon can in principle be identified in the TRT but with a much worse resolution

=> need well-separated e+e- tracks, difficult for a high pT photon
Photon-id at ATLAS: ECAL Layer 1

Both converted/unconverted photons deposit energy in ECAL with a specific shower shape

In the 1st layer of ECAL, the energy needs to be within few strip cells to be identified as a single photon
If it’s not registered at layer 1, the showering will not be identified as a photon.

No more than 20% energy should be inside the HCAL.
Faking Photon by a displaced dark photon

Need to decay after the 1st layer of Pixel
Decay between $34 < r < 400$ mm

A fake converted photon
Decay between $400 < r < 1500 \text{ mm}$

Converted photon if the e$^+$e$^-$ separation is small
Decay before the **ECAL Layer 1**

If $e^+e^-$ is within a strip cell, it will definitely be identified as a single object.

Dark photon can decay close to the strip cells, making it easier to enter a single strip cell.

Magnetic bending $\sim<1 \text{ cm}$

$$\Delta \eta = 0.003 \quad (\Delta \eta \sim 0.01 \text{ in CMS})$$
Decay probability by region

$$\Phi(750) \rightarrow 2\gamma', \quad \gamma' \rightarrow e^+ e^- \quad m_{\gamma'} = 100 \text{ MeV}$$

$$\epsilon = 10^{-3.5}, \quad \epsilon = 10^{-4}, \quad \epsilon = 10^{-4.2}, \quad \epsilon = 10^{-4.5}$$

Before Tracker
\[ r_{\perp} < 34.3 \text{ mm} \]
Converted $\gamma$
\[ 34.3 < r_{\perp} \leq 400 \text{ mm} \]
Unconverted $\gamma$
\[ 400 \leq r_{\perp} \leq 1500 \text{ mm} \]
ECAL & after
\[ 1500 < r_{\perp} \]
Probability of e+e- entering one strip cell

![Graph showing the probability of e+e- entering one strip cell as a function of the proper decay length. The graph includes a curve for different values of $m_{\gamma'} = 200$ MeV, with each curve labeled for the corresponding γ' Proper Decay Length [m]. The y-axis represents the probability of $\Delta x$ in Layer 1 < 4.7 mm.]

Unconverted $\gamma$ faking
Photon faking probability

converted + unconverted γ-faking

$m_\gamma = 50$ MeV
$m_\gamma = 100$ MeV
$m_\gamma = 200$ MeV
Faking a photon at CMS: it’s easier

1st layer Pixel
44 mm (34)

Resolution
$\Delta \eta \sim 0.01$

ECAL location
1.79 m (1.59)
Distinguish the Dark & SM photons
Number ratio of converted vs. unconverted

SM conversion depends on the material,
the dark photon conversion depends on lifetime

CSC NOTE - PHOTON CONVERSIONS IN ATLAS

Assume \( N_{sg} = N_{bg} = 11 \) at 3.2 fb\(^{-1}\)

Photon conversation rate \(~ 20\%\)

Can eventually tell the difference
Energy ratio between the converted $e^+e^-$

SM photon conversion tends to give leptons with asymmetric energy

$$\gamma + A \rightarrow e^+e^- + X$$

Can we use this to distinguish the SM/Dark photon decays?

$$\frac{d \text{Prob}_\gamma}{dx} \propto \left[ 1 - \frac{4x}{3(1 + x)^2} \right] / (1 + x)^2$$
Not that easy…

When the dark photon is mainly produced in the transverse mode, its decay also generates an asymmetric electron energy.

\[
\frac{d\text{Prob}_\gamma}{dx} \propto \left[1 - \frac{4x}{3(1 + x)^2}\right]/(1 + x)^2
\]

\[
\frac{d\text{Prob}_\gamma}{dx} \propto \left[\frac{2}{3} - \frac{4x}{3(1 + x)^2}\right]/(1 + x)^2
\]
If dark photon decays cannot fake the unconverted

e.g. ECAL only exclusion from the photon jet information

Ellis, Roy, Sholtz (12') \( \eta F_{\mu\nu} F^{\mu\nu} \), \( \mathcal{T} \) N-subjettiness variable

Dasgupta, Kopp, Schwaller

The bound can be much stronger

However, it is not clear how well does the same bound apply to the dark photon case, since the \( e^+e^- \) from the dark decay carrying asymmetric energy
Complimentary search

Constrain decays outside the photon id region

\[ \Phi(750) \rightarrow 2\gamma', \quad \gamma' \rightarrow e^+e^- \quad m_{\gamma'} = 100 \text{ MeV} \]

\[ \epsilon = 10^{-3.5}, \quad \epsilon = 10^{-4}, \quad \epsilon = 10^{-4.2}, \quad \epsilon = 10^{-4.5} \]

- Prompt lepton jet
- Displaced lepton jet
- Monophoton + MET
When dark photons decay before the Pixel, there are jets of highly collimated electrons. The search of "lepton jets" can be applied.

Reconstruction efficiency of two 100 GeV LJs $\sim 0.36$. We estimate the bound by requiring $< 15$ 2eLJs events (90%CL) @ 8 TeV.
2 $\gamma_d$ after ECAL: displaced lepton-jet

Reconstruction efficiency of 30 GeV LJs $\sim 0.1$
100 GeV LJs $\sim 0.5$

Even for 750 GeV decays into 2 LJs, the bound is still much weaker than 10 fb @ 8 TeV (corresponds to 45 fb @ 13 TeV if it’s diphoton)
1 fake $\gamma + \gamma d$ after ECAL: mono-photon + MET

$\gamma$ $p_T > 150$, $|\eta| < 1.37$

CERN-PH-EP-2014-245 (ATLAS 8 TeV monophon)

The vector momentum imbalance in the transverse plane is obtained from the negative vector sum of the reconstructed and calibrated physics objects and is referred to as missing transverse momentum, $E_T^{\text{miss}}$. The sym-
Apply to the 750 GeV diphoton

Curves: $\sigma \times Br(\Phi \to 2\gamma)$ @ ATLAS 13 TeV
Shaded (Left): 90% CL exclusion bound, $\gamma+$MET search @ ATLAS 8 TeV
Shaded (Right): 90% CL exclusion bound, prompt LJ search @ ATLAS 8 TeV

Monophoton
Prompt LJs

Curtin, Essig, Gori, Shelton 1412.0081
Lifetime-dependent Angular Distribution

Higgs spin analysis 1209.5263
Slower decay fakes more forward signal
Fake a higher spin resonance from a lower spin
Application to the 750 GeV physics

Roberto Vega-Morales
Challenges in generating the 750 GeV signal

Large signal requires light or largely e-charged mediators
Much weaker constraints on darkly-charged mediators

Bound from the Z+gamma search
The resonance can have a highly suppressed coupling to Z
Additional feature

Fake the higher spin resonance

Allows the spin-1 resonance decay

\[
\frac{e g_d g_H}{16\pi^2 M^2} F_{V_H}^{\mu\nu} F_{\nu}^{\alpha} F_{\alpha\nu}^{'}
\]

Vector bound state of EW-charged quirks, usually suffers a strong e+e- constraint if 750 is the pseudo-scalar.
Conclusion

Dark signals may be around us!
Fake photons from the dark photon decays is a good example

The fake SM signals can explain the weird signals
e.g., easier 750 explanation, non-trivial angular distribution

We can distinguish these signals eventually,
but some works are required

When study collider constraint on dark photon decays,
part of the signals may be identified as SM photons