Photon-Jets

Jets and Photons, arXiv:1210.1855
Phenomenology of Photon-Jets, arXiv:1210.3657

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Using Jet Substructure @ Terascale

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Work done with
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Photon-jet
- a collection of two or more collinear photons, that form a jet like deposition in the calorimeters
We will try to separate these three categories:

- Photon-Jet
- Photon
- QCD-Jet
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Photon-jets are both photon-like and jet-like, therefore we need a new category.
If we want to compare QCD-jets, photon-jets and photons, we need a common basis.
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\[
\text{Jets} = \left\{ \text{some jets}, \text{some other jets}, \ldots \right\}
\]
Outline

1 Model

2 Analysis

3 Discriminants

4 Results

5 Conclusion
EFT Model

- Take the Standard model

\[ \mathcal{L} = \mathcal{L}_{SM} \]
EFT Model

- Take the Standard model
- Add two scalars in the Hidden Sector:

\[
\begin{array}{c|cc}
 n_1 & Q & SU(3)_C & SU(2)_W \\
 n_2 & 0 & 1 & 1 \\
\end{array}
\]

\[
\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Kin} + \frac{1}{2} m_1^2 n_1^2 + \frac{1}{2} m_2^2 n_2^2
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- Allow the lighter scalar to decay into photons.

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  |-------|--------|-------------|
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  | \( n_2 \) | 0      | 1           | 1            |

- Allow decays within the Hidden sector.
- Allow the lighter scalar to decay into photons.
- Mix the heavier scalar with the Higgs.

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\]
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EFT Model: Why? An Example

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- As an example take MSSM with a chargino $\chi^{\pm}$.

$L = M_{\chi} + \chi^{-} + \lambda n_{\chi}^{2} + \chi^{+}$.
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As an example take MSSM with a chargino $\chi^\pm$.

\[ \mathcal{L} = M\chi^+\chi^- + \lambda n_2 \chi^+\chi^- . \]

We can integrate out the $\chi^\pm$, its loops give us the right photon vertex:

\[ \frac{\lambda e^2}{16\pi^2 M} \rightarrow \frac{1}{4\Lambda} \]
Take the allowed interactions...
Take the allowed interactions...and let the Higgs decay.
What does it take to make a Photon-Jet?

- It takes the right set of masses for $n_1$ and $n_2$.
- We will use $(m_1, m_2) \in \{(5, 1), (10, 0.5)\}$ GeV. However, in the PRD paper we develop a larger benchmark set.
- All decays are prompt.
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![Diagram of Photon-Jet configurations]
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3. Discriminants

4. Results

5. Conclusion
Our Calorimeters

\[ \frac{\sigma}{E} = 10\% / \sqrt{E} + 1\% \]

\[ \frac{\sigma}{E} = 50\% / \sqrt{E} + 3\% \]
1. Use Pythia 8 to generate both signal and background events (Turn on ISR, FSR and MI).

2. Deposit particle energy according to their type and momenta. (We simulate transverse showers for photons - the pattern on the right corresponds to Molière radius in Pb)

3. Recover massless four-vectors from \((\eta, \phi, E)\) of each cell in both calorimeters.

4. Find jets in the union of all four vectors with Anti-\(k_T\), \(\Delta R = 0.4\), \(p_T > 50\) GeV.
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These discriminants will be used in a multivariate analysis (TMVA) to separate all three populations:

- Conventional
  - Fraction of Hadronic Energy in the Jet
  - Number of Charged Tracks
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- N-subjettiness

- More Substructure
  - Energy-Energy Correlation
  - Subjet Spread
  - Subjet Fractional Area
  - Leading subjet $p_T$
Fraction of Hadronic Energy in the Jet

Measures the fraction of hadronic energy in a jet, \( \theta = \frac{E_{\text{had}}}{E_{\text{total}}} \)
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We determine if a track is associated with a jet by including its softened four-vector with all the calorimeter four-vectors.
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![Histogram of Number of Charged Tracks]
N-subjettiness

- Take a jet. Find $N$ subjets, through reverse clustering. This defines $N$ axes.

- Form a sum:

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{1,k}, \ldots, \Delta R_{N,k} \}$$

where $k$ runs over all the constituents of a jet and $\Delta R_{i,k}$ is the angular distance between $k$-th constituent and the $i$-th subjet.
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- Find $N$ subjets (by reverse clustering) with a particular jet algorithm ($k_T$, $C/A$).

Each variable therefore has the form $\text{var}(N, n, \text{algorithm}).$
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- Find \( N \) subjets (by reverse clustering) with a particular jet algorithm \((k_T, C/A)\).
- If you are performing a sum, sum only over some number \( n \leq N \) of the highest \( p_T \) subjets (effectively filtering)

\((N, n) = (5, 3)\) works well for our photon-jets.

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- Each variable therefore has the form $var(N, n, \text{algorithm})$. 

![Diagram showing jet substructure]
Leading Subject Transverse Momentum

\[ Lp_T = \frac{p_T \text{ of the hardest subjet}}{p_T \text{ of the entire jet}} \]

Since QCD is characterized by soft radiation we expect the leading subjet will contain most of the \( p_T \) of the jet.
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\[ \text{Frequency dominated by one subjet} \]

\[ \text{CA} \]

\[ \text{Frequency dominated by one subjet} \]

\[ \text{K} \]

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Energy-Energy Correlation

\[ \sum E^2 = \sum_{i<j} E_i E_j / E_{total}^2 \]

Relates to the variance of energy distribution amongst the subjets.
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Subjet Spread

\[ \sum R_{ij} = \sum_{i<j} \sqrt{\Delta \phi_{i,j}^2 + \Delta \eta_{i,j}^2} \]

Measures the spread of subjets within the jet.
Subject Spread

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Fractional Area is defined as the sum of active areas of the $n$ hardest subjets divided by the total (active) area of the jet. (We use the FastJet implementation, only $C/A$)
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$$\delta_J = \frac{\sum_i A_i}{A_J}$$

(1)
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We train a BDT to separate photon-jets from QCD-jets.
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We train another BDT to separate Photon-Jets from Photons.

**Photon vs Photon Jet**

- **Frequency** vs **BDT response**

**Acceptance** vs **Fake Rate**

- **Photon vs Photon Jet**
- **Conventional**
- **Conventional + Substructure**

*J. Scholtz (UW)*

**Separating Photon-Jets and Photons**
We train another BDT to separate Photon-Jets from Photons.
We can also look at the QCD-jets faking photons:

![Graph showing the correlation between acceptance and fake rate.](image)
We use two BDTs to extract as much information as possible.

Split QCD-jets away with *only Conventional* variables.

Split Photons from photon-jets with *just Substructure*.

QCD-jets photons photon-jets.
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This analysis is possible because we treat all objects on equal footing.
BACKUP SLIDES
More study points

Photon-jet vs QCD, (Our example is PJSP6)

Photon-jet vs Photon
Charged Tracks vs $\theta$

![Graph showing charged tracks vs $\theta$](image)

- $J_{QCD}$
- $\gamma$
- $j_{\gamma} (5,1)$
- $j_{\gamma} (10,0.5)$

Number of Charged Tracks

Frequency

0 1 2 3 4 5 6 7 8 9 10

0.0 0.2 0.4 0.6 0.8

Number of Charged Tracks ($\theta<0.025$)

Frequency

0 1 2 3 4 5 6 7 8 9 10

0.0 0.2 0.4 0.6 0.8 1.0
Substructure for different masses

![Graphs showing substructure for different masses](image)
Substructure for different masses II

- $\log_{10}(1-Lp_T(CA))$
- $\log_{10}(1-Lp_T(kT))$
- $E^2(CA)$
- $E^2(kT)$

Legend:
- (10,1)
- (10,0.5)
- (5,1)
- (5,0.5)
- (2,0.5)
- QCD
Substructure for different masses III

![Graphs showing distributions of substructures for different masses](image-url)
Conversions

Opacity of the Pixel section of the ATLAS tracker

Data Points
Interpolation

\( \frac{x}{\lambda_0} \)

\( \eta \)

 Radiation length \( (X_0) \)

- Services
- TRT
- SCT
- Pixel
- Beam-pipe
$$ct \sim c m_h \pi \left( \frac{8}{\mu^2} + \frac{\Lambda^2}{m_2^4} \right)$$