Photon-Jets

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

Jakub Scholtz

Harvard

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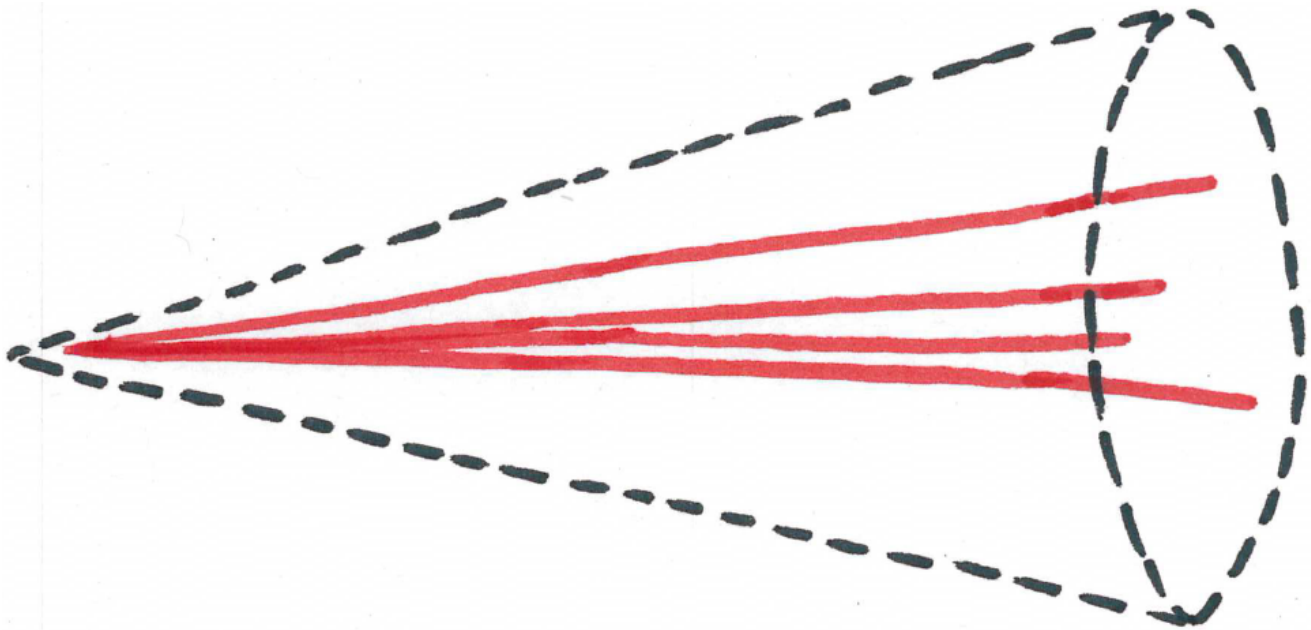
Searching for Exotic Hidden Signatures with ATLAS in LHC Run 2
Cosenza

Work done with
Stephen D. Ellis, Tuhin S. Roy

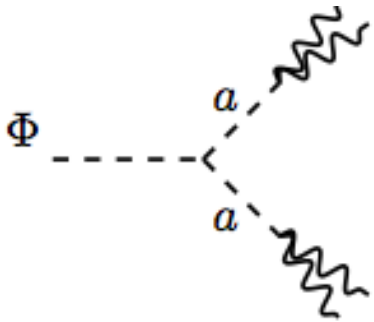
Photon-jet

- a collection of two or more collinear photons, that form a jet like deposition in the calorimeters

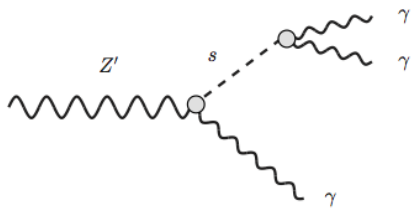


750 GeV Excess Introduction/Motivation

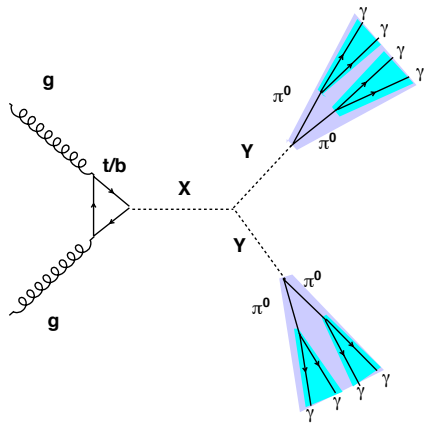
Amongst the deluge of papers, there were possible explanations for the excess that use the idea of Photon-Jets:



1512.04928
1512.05775
1512.06671
1512.08497
...



1512.06833
...?



1602.00949
...?

750 GeV Excess and Higgs

Since this new resonance and the Higgs might mix, we might expect Photon-Jets in both samples (with different cross-sections)

m_a	$R_{\gamma\gamma}(h(125))$	$R_{\gamma\gamma}(\Phi(750))$
0.5 GeV	0.016	0.0026
1 GeV	0.032	0.0053
2 GeV	0.064	0.01
4 GeV	0.128	0.02

Motivation

- Apart from the 750 GeV excess...
- Photon-jets have been suggested as the source of (now gone) $h \to \gamma\gamma$ excess by various groups: Dobrescu, Landsberg and Matchev; Draper and McKeen as well as Toro and Yavin.
- Some photon-jets will always leak into the tagged photon sample.
- On the other hand, our current photon identification may be so tight, it may be throwing away photon-jets – we could be throwing away a possible signal of new physics.
- Photon-jets are both photon-like and jet-like, therefore we need a new category.

Previous Work

Photon-jets have been suggested by various groups:

B. A. Dobrescu, G. L. Landsberg, and K. T. Matchev, "Higgs boson decays to CP odd scalars at the Tevatron and beyond," *Phys. Rev.* **D63** (2001) 075003, arXiv:hep-ph/0005308 [hep-ph].

S. Chang, P. J. Fox, and N. Weiner, "Visible Cascade Higgs Decays to Four Photons at Hadron Colliders," *Phys. Rev. Lett.* **98** (2007) 111802, arXiv:hep-ph/0608310 [hep-ph].

N. Toro and I. Yavin, "Multiphotons and photon jets from new heavy vector bosons," *Phys. Rev.* **D86** (2012) 055005, arXiv:1202.6377 [hep-ph].

P. Draper and D. McKeen, "Diphotons from Tetraphotons in the Decay of a 125 GeV Higgs at the LHC," *Phys. Rev.* **D85** (2012) 115023, arXiv:1204.1061 [hep-ph].

S. D. Ellis, T. S. Roy, and J. Scholtz, "Jets and Photons," *Phys. Rev. Lett.* **110** no. 12, (2013) 122003, arXiv:1210.1855 [hep-ph].

S. D. Ellis, T. S. Roy, and J. Scholtz, "Phenomenology of Photon-Jets," *Phys. Rev.* **D87** no. 1, (2013) 014015, arXiv:1210.3657 [hep-ph].

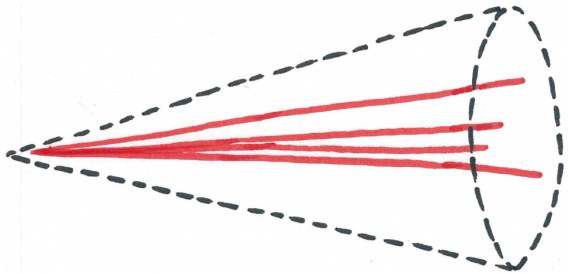
D. Curtin *et al.*, "Exotic decays of the 125 GeV Higgs boson," *Phys. Rev.* **D90** no. 7, (2014) 075004, arXiv:1312.4992 [hep-ph].

And looked for:

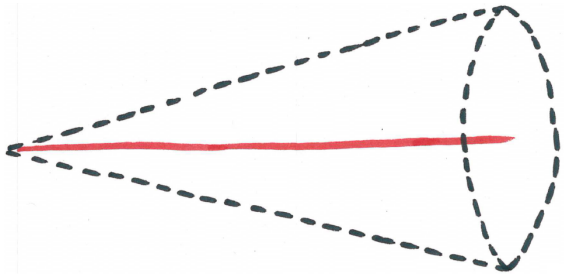
ATLAS Collaboration, G. Aad *et al.*, "Search for new phenomena in events with at least three photons collected in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," arXiv:1509.05051 [hep-ex].

ATLAS Collaboration, "Search for a Higgs boson decaying to four photons through light CP-odd scalar coupling using 4.9 fb^{-1} of 7 TeV pp collision data taken with ATLAS detector at the LHC,". ATLAS-CONF-2012-079

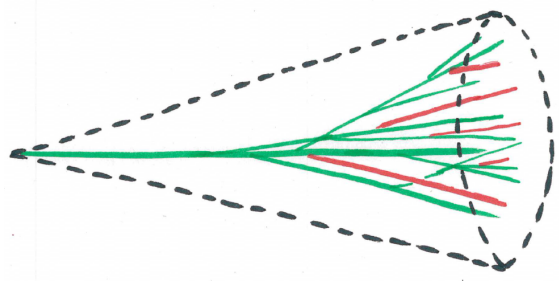
We will try to separate these three categories:



Photon-Jet



Photon



QCD-Jet

Part of the Answer

- If we want to compare QCD-jets, photon-jets and photons, we need a common basis.
- Right now, we search for photons one way (use seeds, calorimeter towers, etc.), for QCD-jets another way (jet algorithms) and don't look for photon-jets at all.
- Instead, search for jets and then tag each of them as either a QCD-jet, a photon or a photon-jet, based on their properties.

$$\text{Jets} = \left\{ \quad , \quad , \quad , \ldots \right\}$$

This talk

- In our study we focused on **four** photon Photon-Jets. We did also study two photon Photon-Jets, but did optimized the search for them.

Study Points	m_1 (GeV)	m_2 (GeV)	μ_{12} (GeV)	η_1	η_2
PJSP **1**	0.5		0	X	
PJSP **2**	1.0				
PJSP **3**	10.0				
PJSP **4**	2.0	0.5	X	0	X
PJSP **5**	5.0	0.5			
PJSP **6**		1.0			
PJSP **7**	10.0	0.5			
PJSP **8**		1.0			

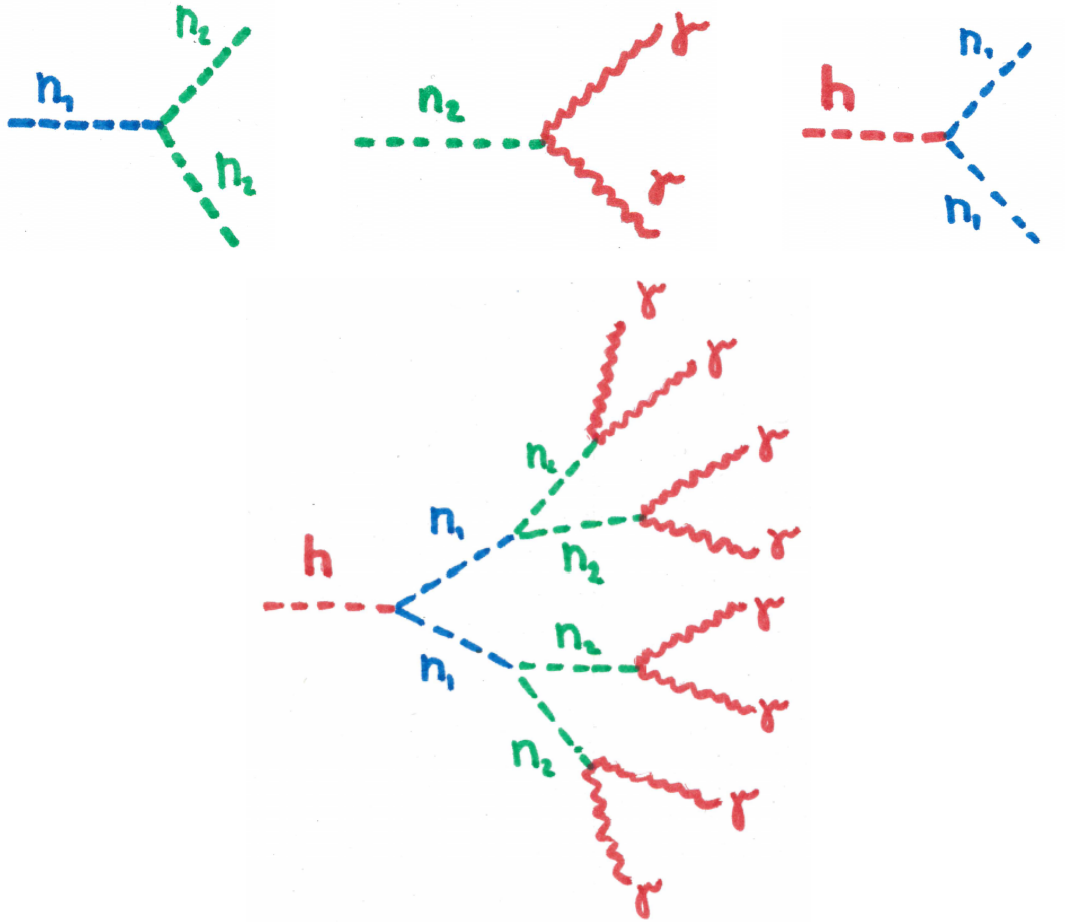
- We focused on **PJSP6**.
- In our analysis all decays are prompt.

Outline

Outline

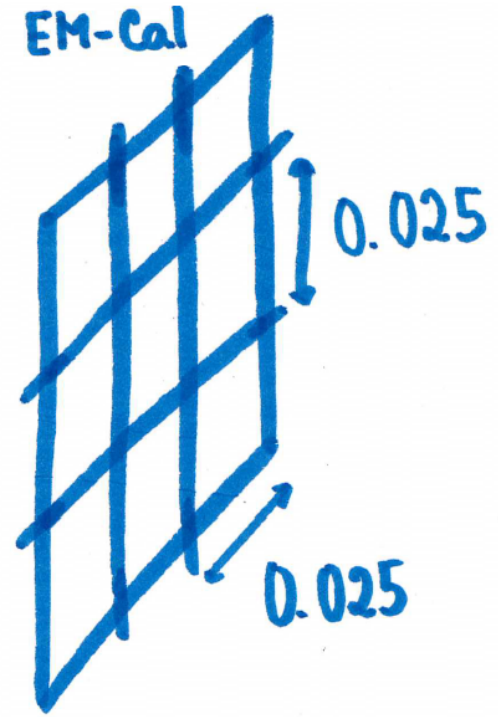
EFT Model

$$\mathcal{L}_{\text{int}} = \tfrac{1}{2} m_1^2 n_1^2 + \tfrac{1}{2} m_2^2 n_2^2 + \tfrac{1}{2} \mu n_1 n_2^2 + \tfrac{1}{4\Lambda} n_2 F^2 + \chi H^2 n_1^2$$

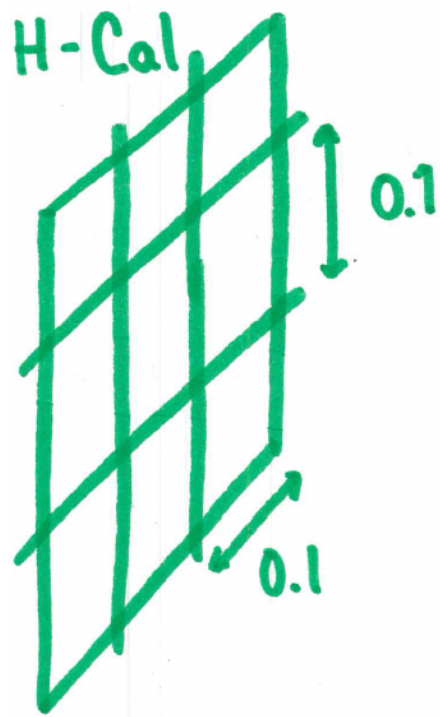


Outline

Our Calorimeters



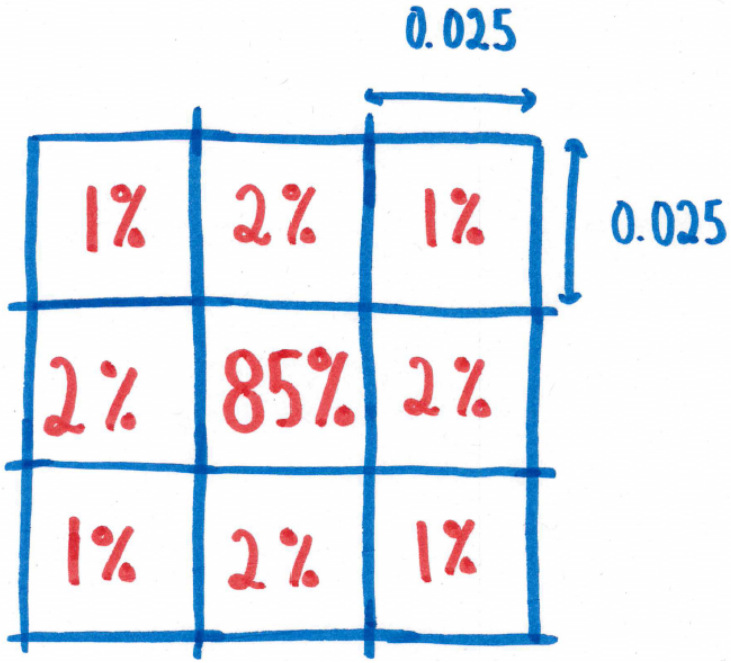
$\sigma/E = 10\%/\sqrt{E} + 1\%$



$\sigma/E = 50\%/\sqrt{E} + 3\%$

Pushing Particles through the Calorimeter

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 (η, ϕ, 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.



Energy deposition pattern for photons in the EM calorimeter.

Outline

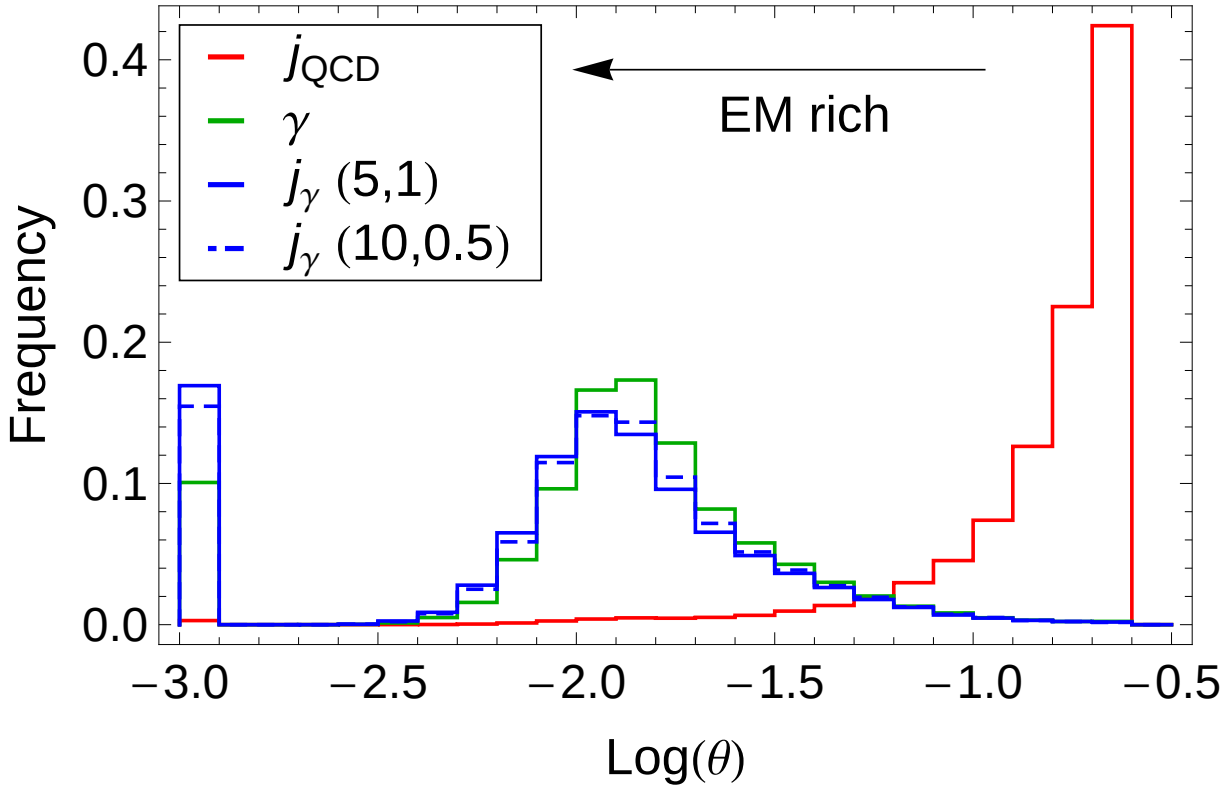
Discriminants

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
- N-subjettiness
- More Substructure
  - Energy-Energy Correlation
  - Subjet Spread
  - Leading subjet p_T

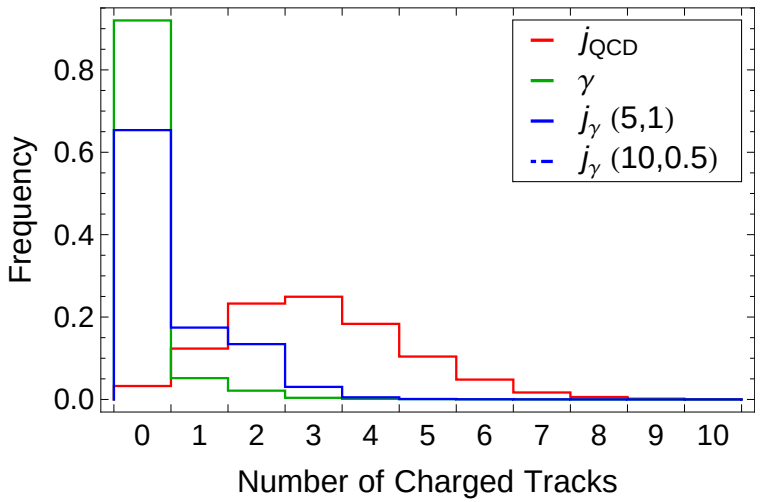
Fraction of Hadronic Energy in the Jet

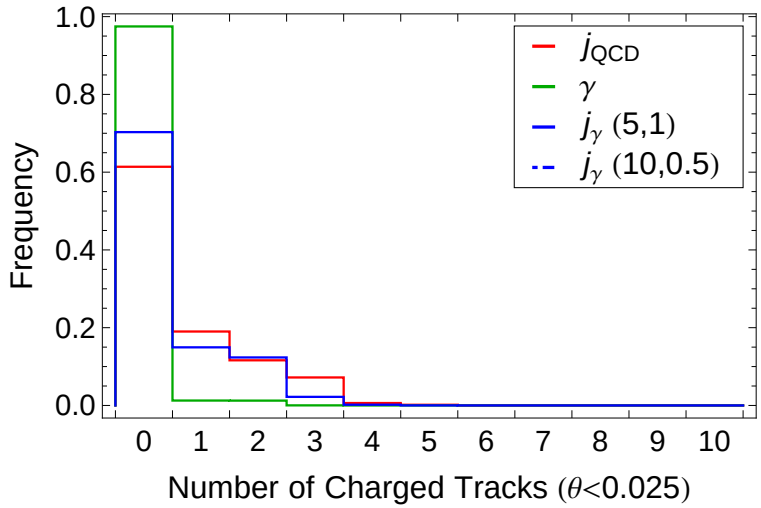
Measures the fraction of hadronic energy in a jet, $\theta = E_{had}/E_{total}$



Number of Charged Tracks

- Counts the number of charged tracks with $p_T > 2$ GeV associated with the jet.
- We determine if a track is associated with a jet by including its softened four-vector with all the calorimeter four-vectors.



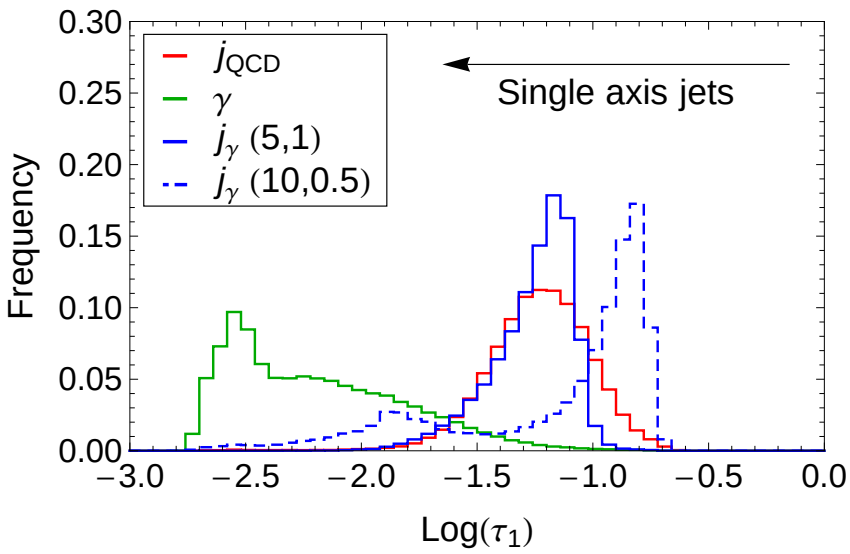


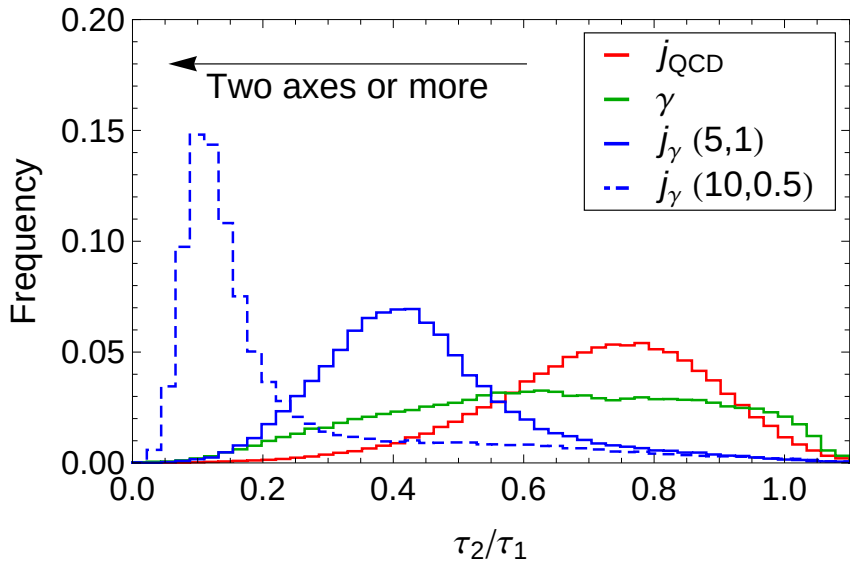
N-subjettiness

- Take a jet. Find N subjets. This defines N axes.
- Form a sum:

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

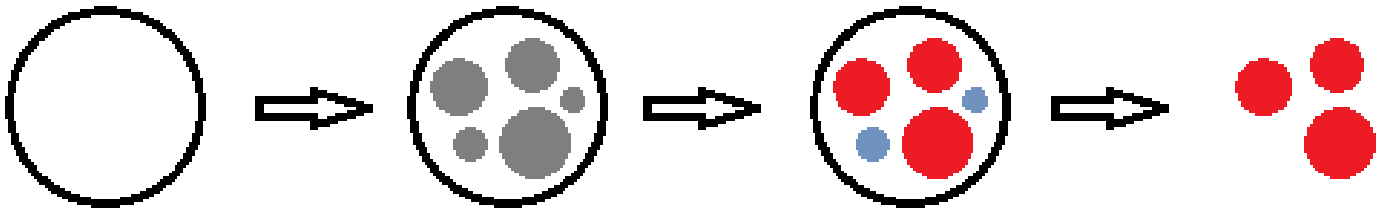
where k runs over all the constituents of a jet and $\Delta R_{i,k}$ is the angular distance between k-th constituent and the i-th subjet.





More Substructure – Grooming

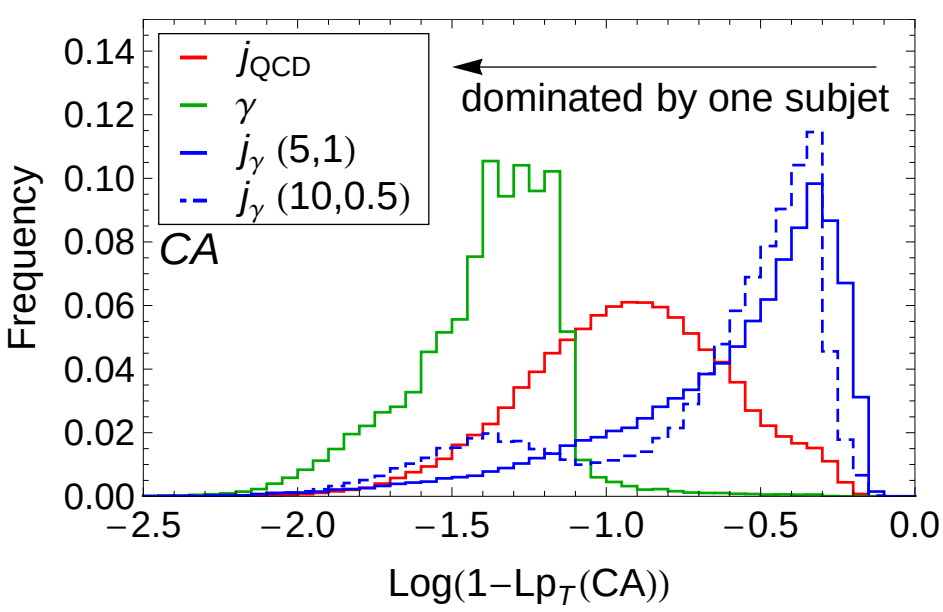
- Take all the constituents of a jet.
- Find N subjets with a particular jet algorithm (k_T, C/A).
- If you are performing a sum, sum only over some number $n \leq N$ of the highest p_T subjets (effectively filtering)
- $(N, n) = (5, 3)$ works well for our photon-jets.
- Each variable therefore has the form $var(N, n, \mathrm{algorithm})$.

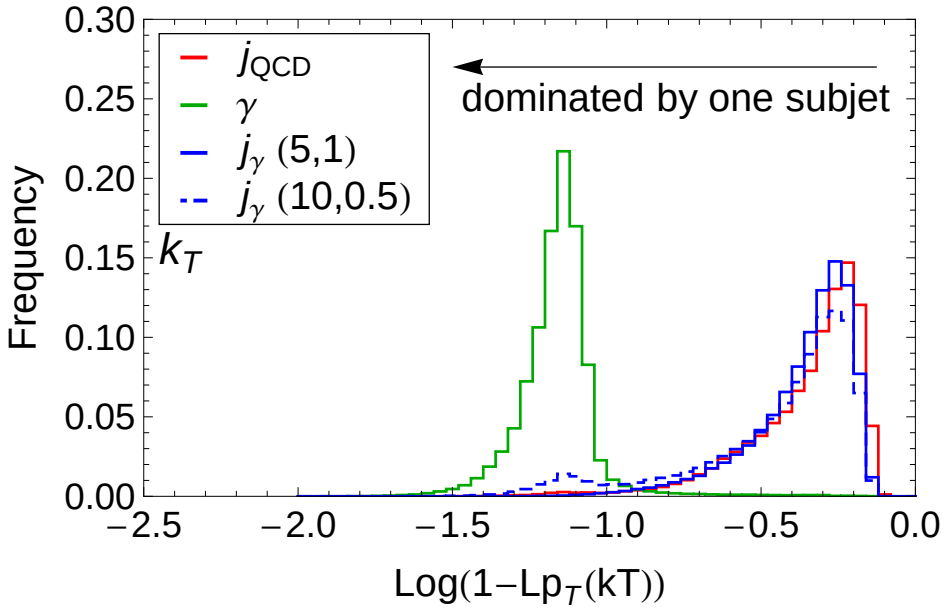


Leading Subjet Transverse Momentum

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

Since QCD is characterized by soft radiation we expect the leading subjet will contain most of the p_T of the jet.

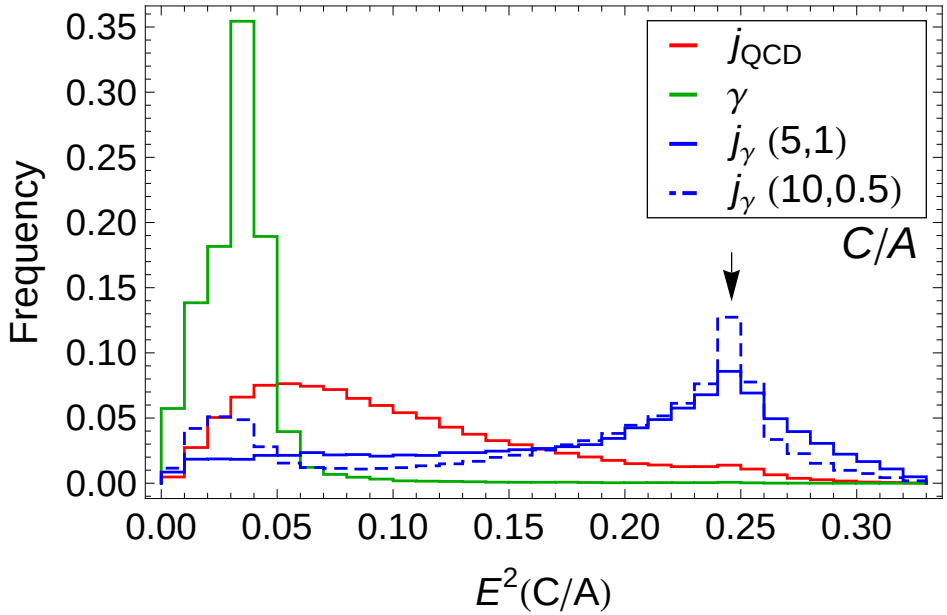


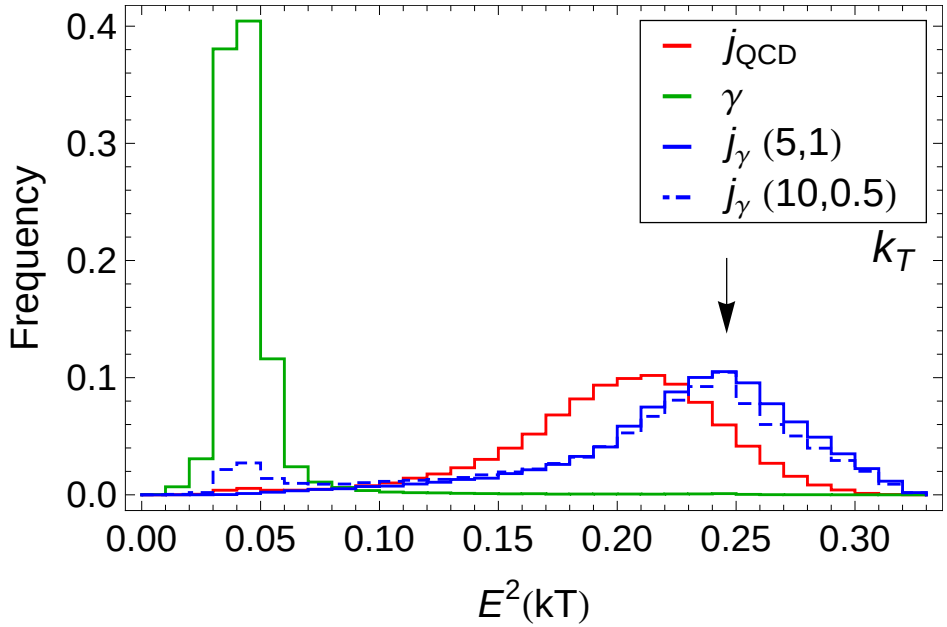


Energy-Energy Correlation

$$\sum E^2 = \sum_{i<j} E_i E_j / E^2_{total}$$

Relates to the variance of energy distribution amongst the subjets.

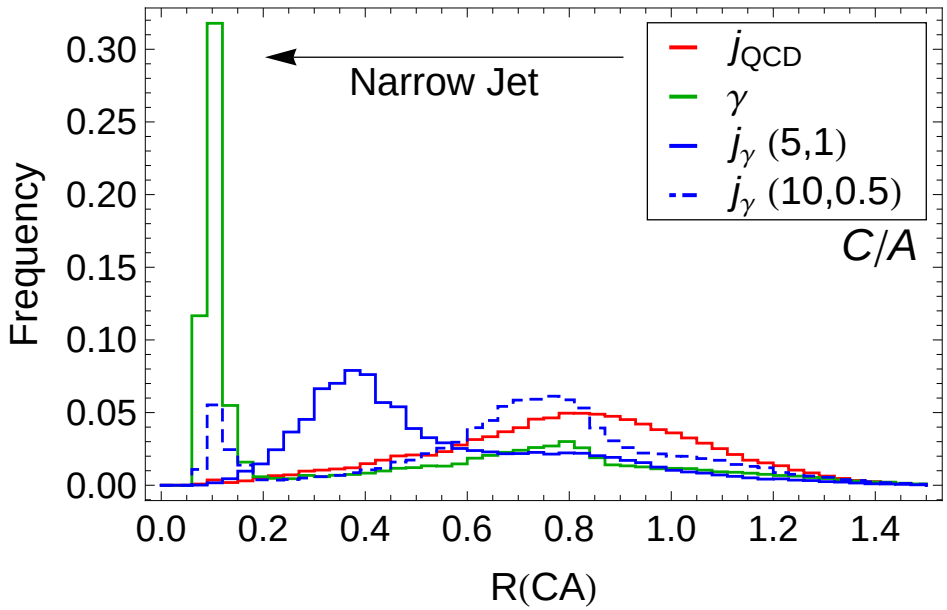


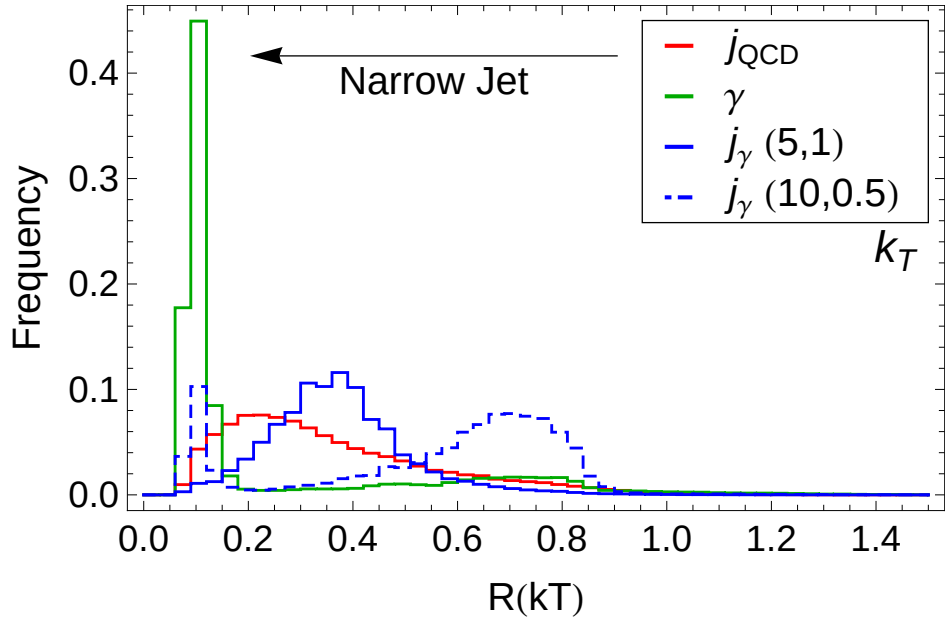


Subjet Spread

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

Measures the spread of subjets within the jet.

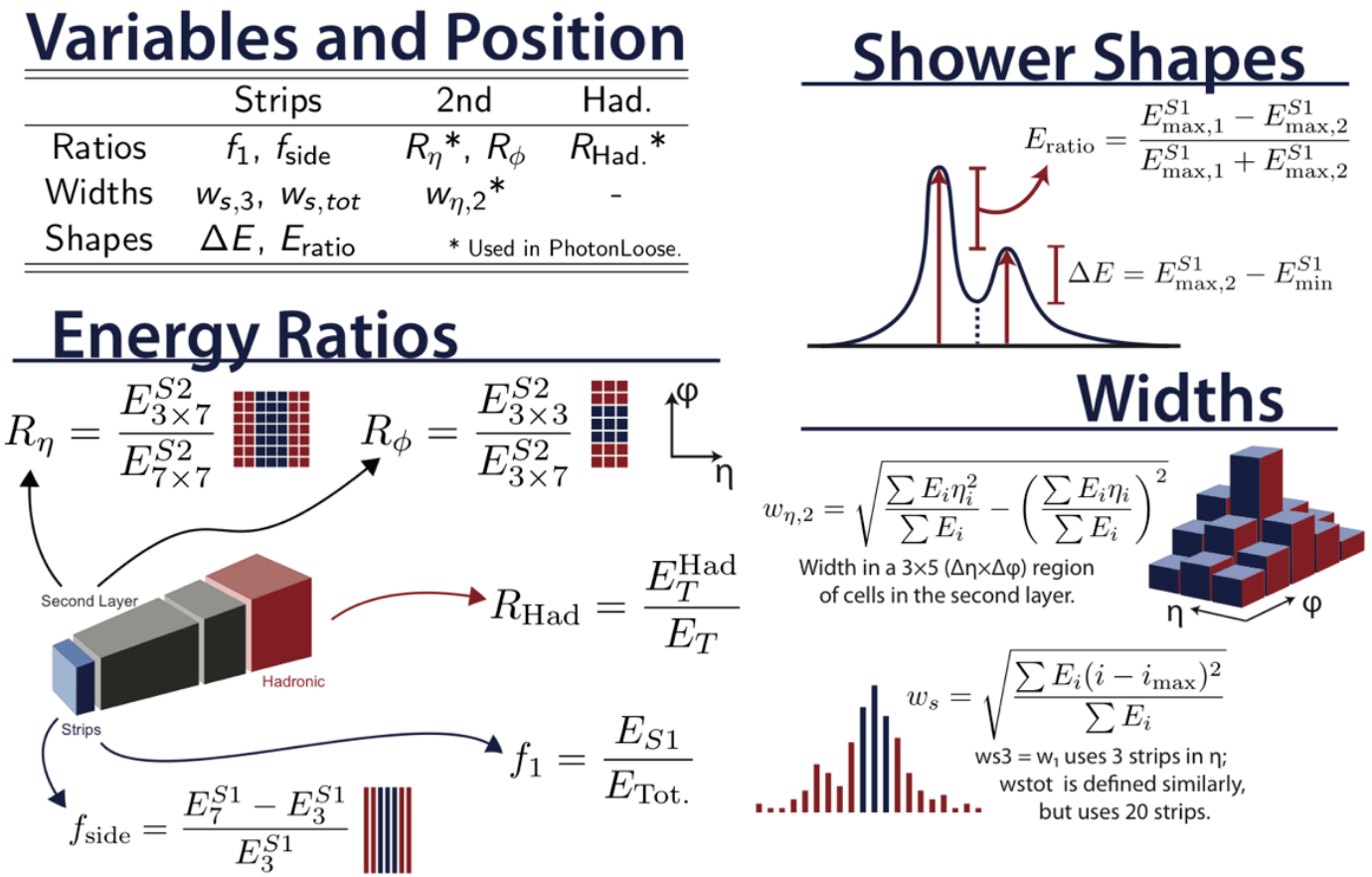




ATLAS photon variables

e/γ performance group: ATL-COM-PHYS-2013-600

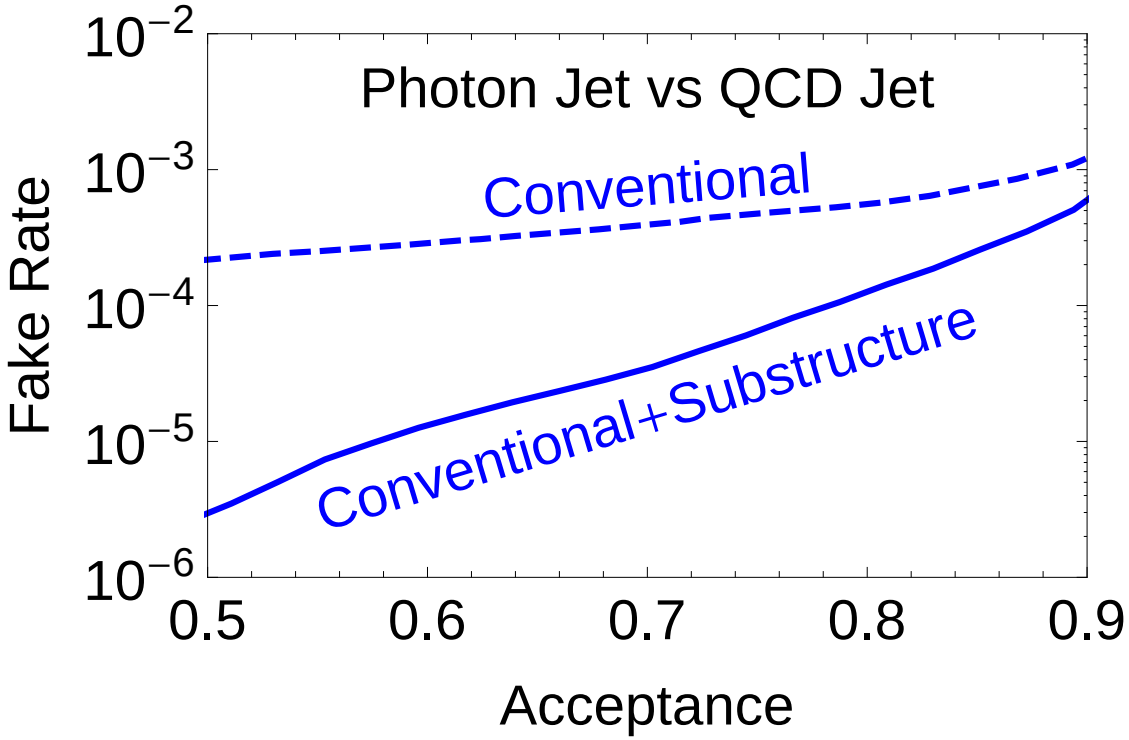
Graphical illustration

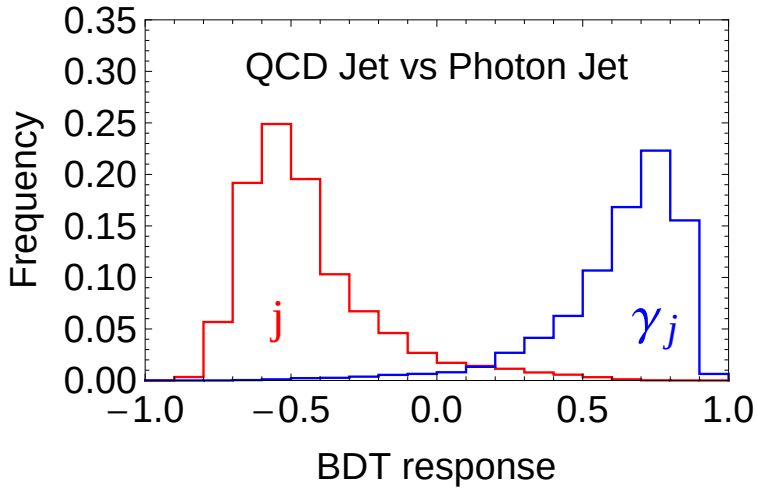


Outline

Separating Photon-Jets and QCD-Jets

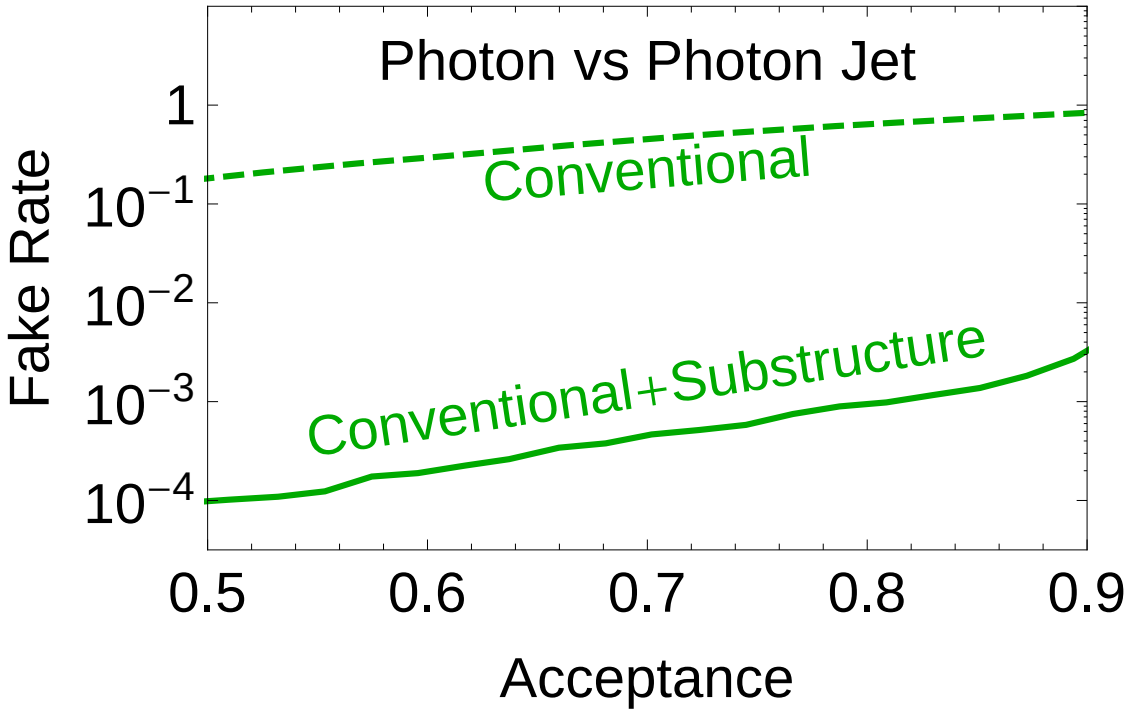
We train a BDT to separate photon-jets from QCD-jets

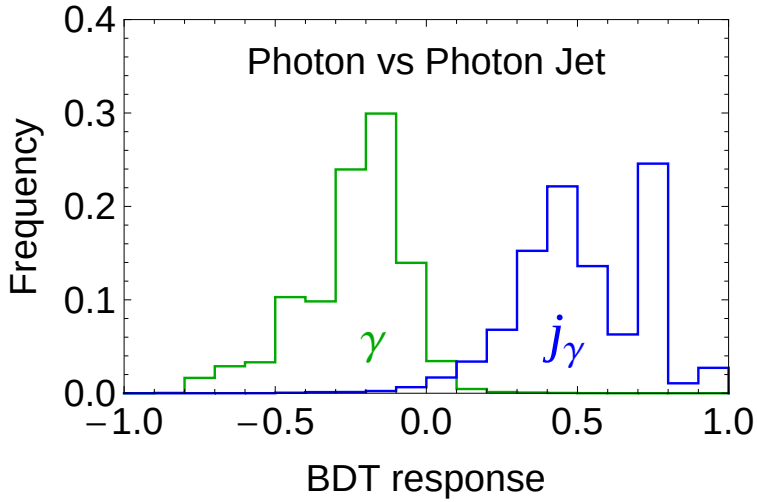




Separating Photon-Jets and Photons

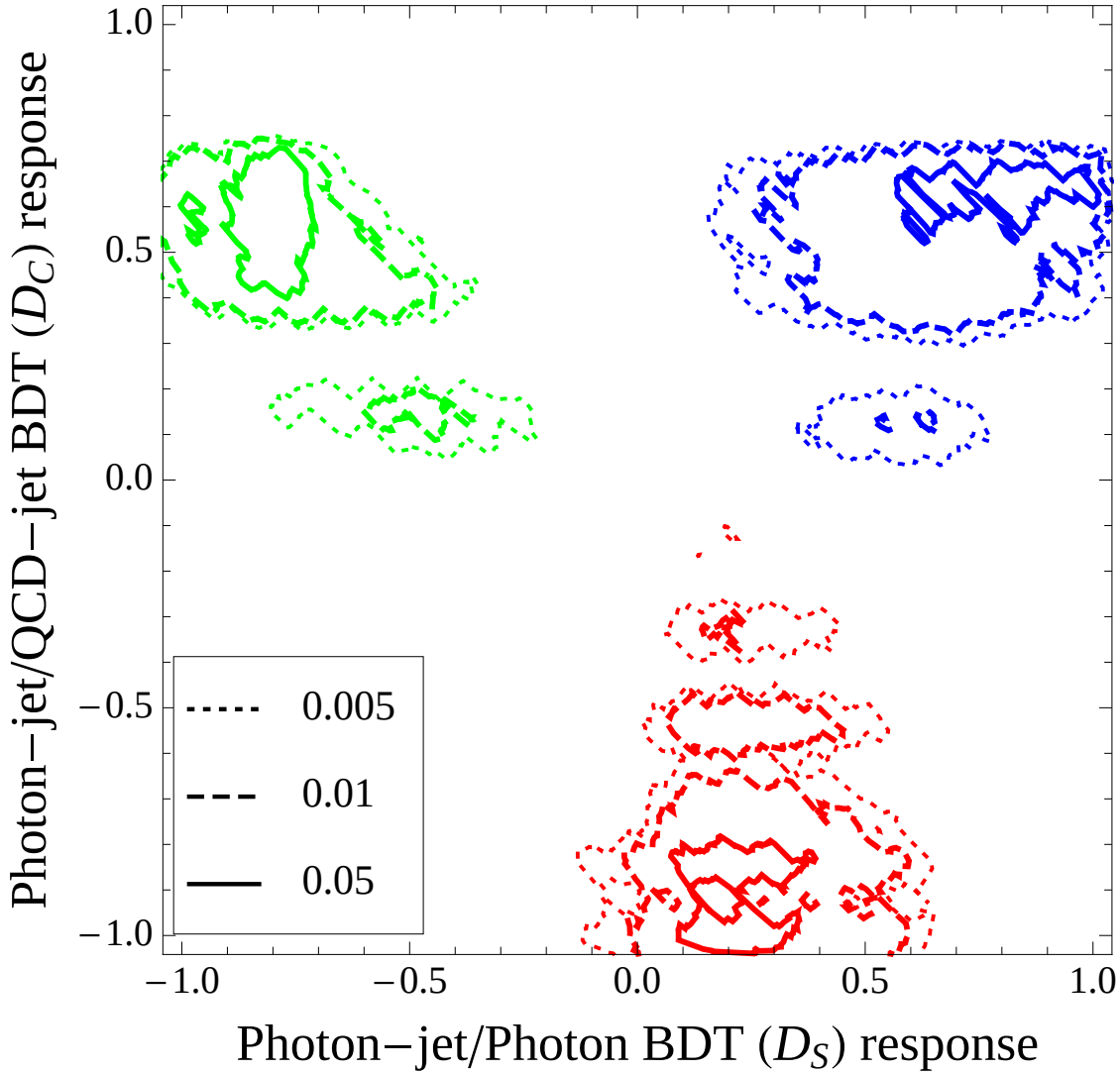
We train another BDT to separate Photon-Jets from Photons



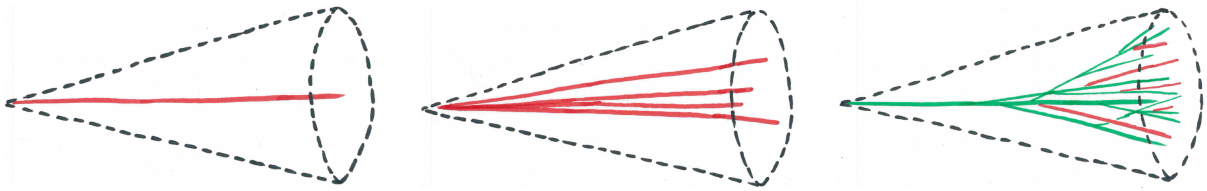


Separating Photons, Photon-Jets and QCD

- 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.



Conclusion

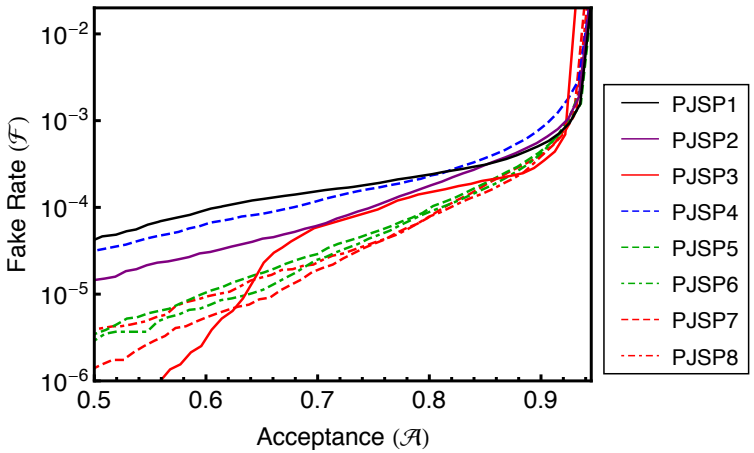


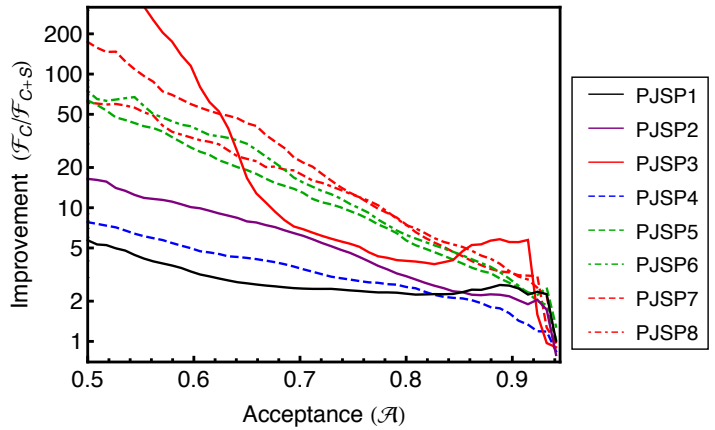
- Detecting Photon-Jets is not just about resolution – it is about looking for them as well.
- We could mis-indentifying photon-jet as jets or photons.
- We could be missing photon-jets by throwing them away.
- Now, we have the tools to separate all three populations – a significant amount of separation comes from substructure of these jets.
- This analysis is possible because we treat all objects on equal footing.

BACKUP SLIDES

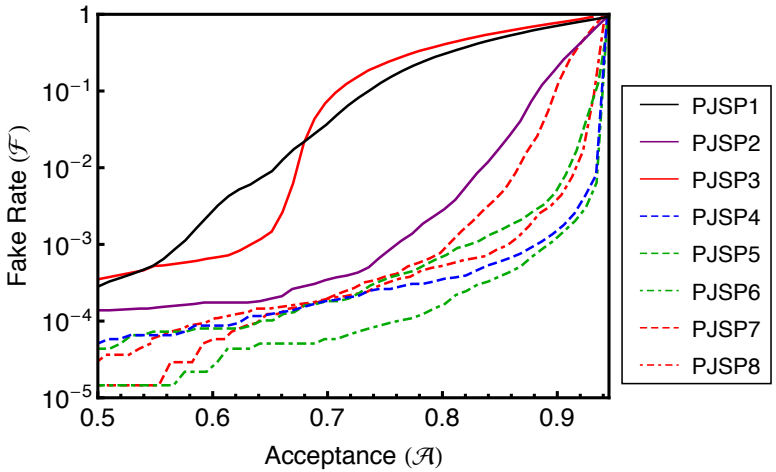
More study points

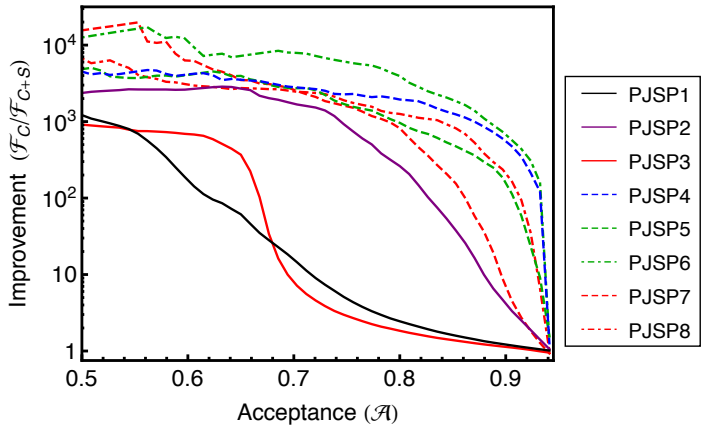
Photon-jet vs QCD, (Our example is **PJSP6**)





Photon-jet vs Photon





Conversions