

DM@LHC Workshop 2020: 5th June

Exploring Jet Substructure in Semi-visible jets

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(Thanks to Tim Cohen and Joel Doss for useful discussions)



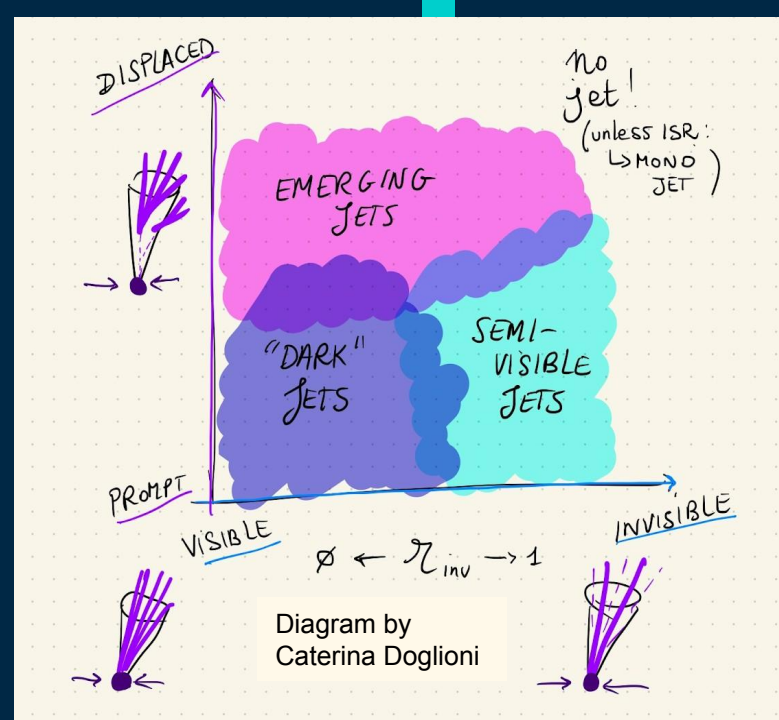
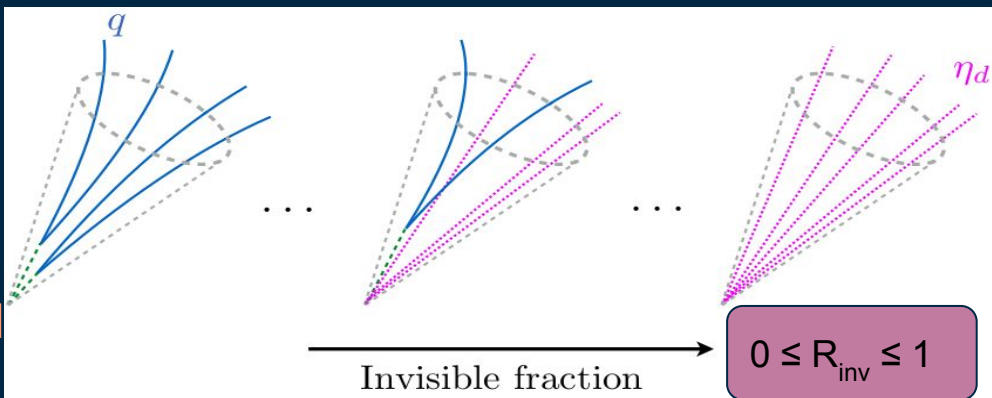
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Introduction

- Look at unusual topologies & hidden phase space corners
- Dark hadrons decay promptly in a QCD-like fashion partially back to visible sector **(semi-visible jets "SVJ")** Initial motivation
 - Showering using Pythia hidden valley module



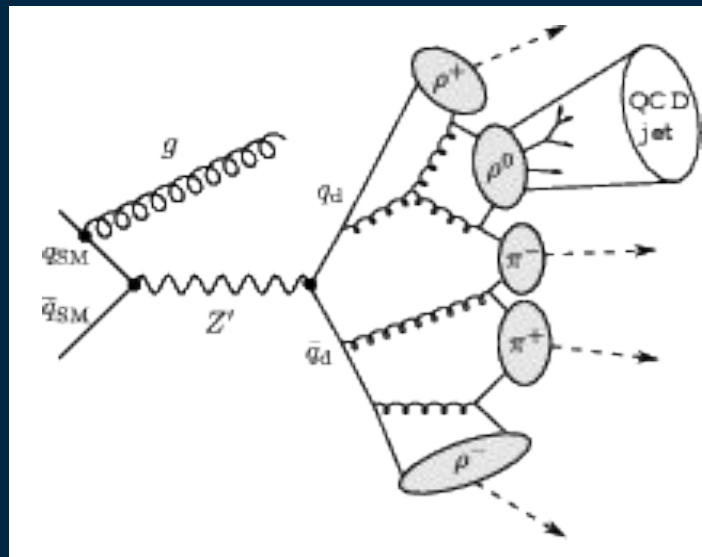
Based on the Paper:
**LHC Searches for Dark Sector
Showers** : Tim Cohen et al [arXiv:
[1707.05326](https://arxiv.org/abs/1707.05326)]



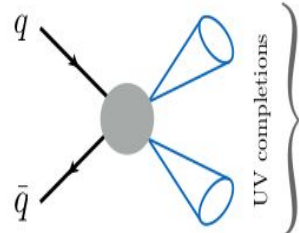
Hidden Valley: Semi-visible jets idea

Two different dark quark flavours

- ▶ Combine to form π^+ , π^- , π^0 , and ρ^+ , ρ^- , ρ^0 (assumed to be produced thrice as much as pions)
- ▶ Only ρ^0 is unstable and (promptly) decays to SM quarks: more likely to decay to b pairs due to need for a mass insertion, to make the angular momentum conservation work out
- ▶ Other mesons are (collider-)stable \rightarrow invisible

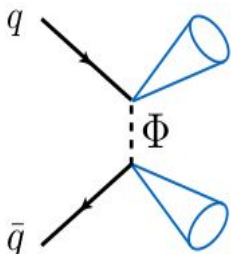


Contact Operator



UV completions

t-channel



Model Parameters:

1. M_ϕ = Mass of Scalar Bi - fundamental (mediator)
2. M_d = Mass of dark hadrons
3. r_{inv} = no. of stable dark hadrons/ no. of hadrons

Choosing $M_\phi = 1.5$ TeV, $M_d = 10$ GeV for the studies

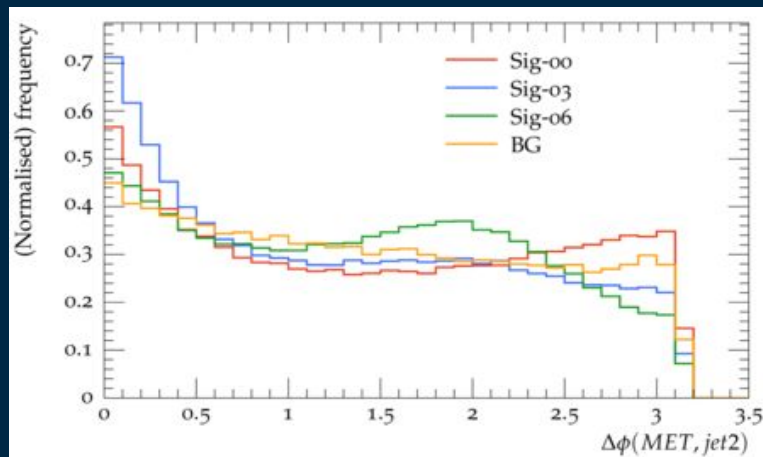
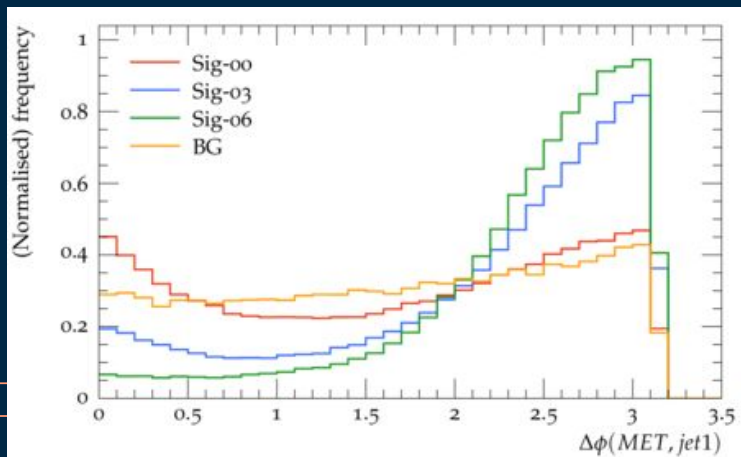
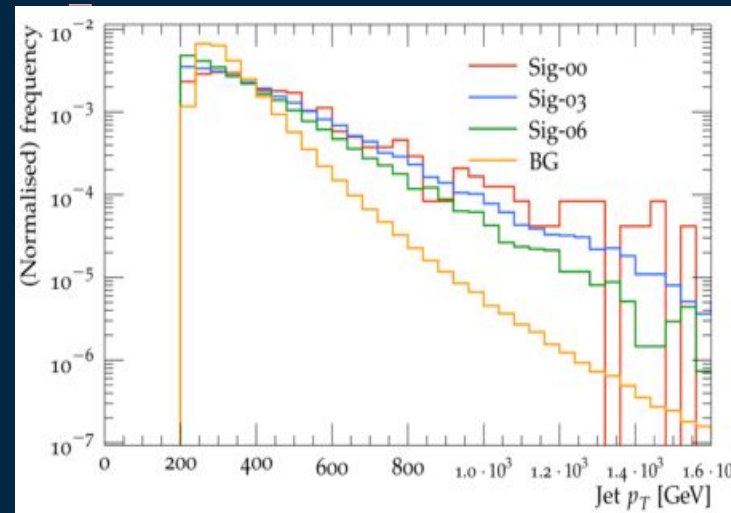
Aim of the study

- Comparing jet substructure variables to see if SVJ substructure is different from light quark/gluon jets (BG). Do they behave more multi-pronged as opposed to mostly single prong?
- Comparison can be done in p_T bins or in m/p_T bins, picked the former, as there is no resonance.

t-channel makes it more challenging as no resonance peak

Looking at jet p_T ; angle between MET & leading/sub-leading jets

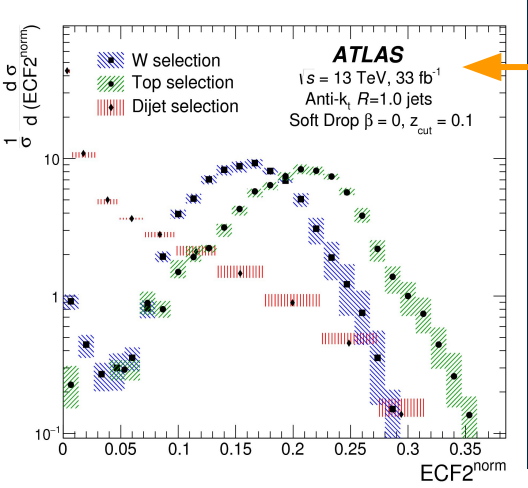
Subleading jets tend to align more with MET, which makes it harder to study



Signals
($r_{\text{inv}} = 0, 0.3, 0.6$) and multijet background generated using MG5 + Py8

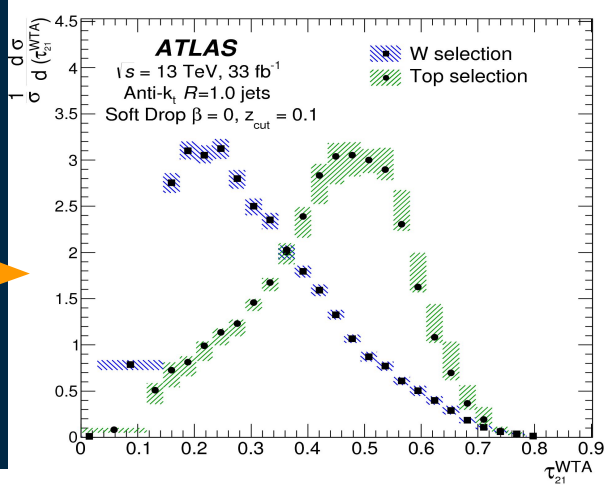
Normally signals are generated with upto two extra jets!

Plots from ATLAS to explain how the JSS variables behave



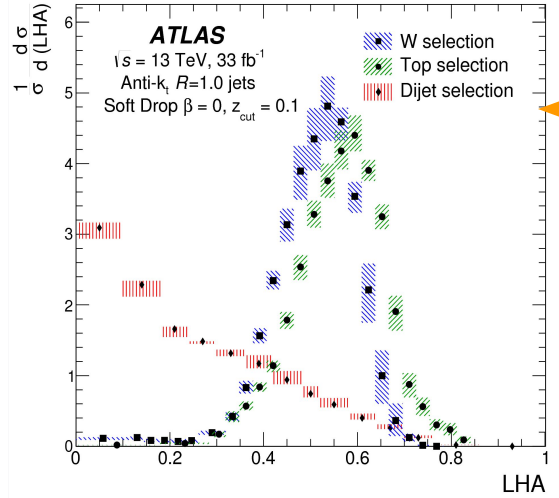
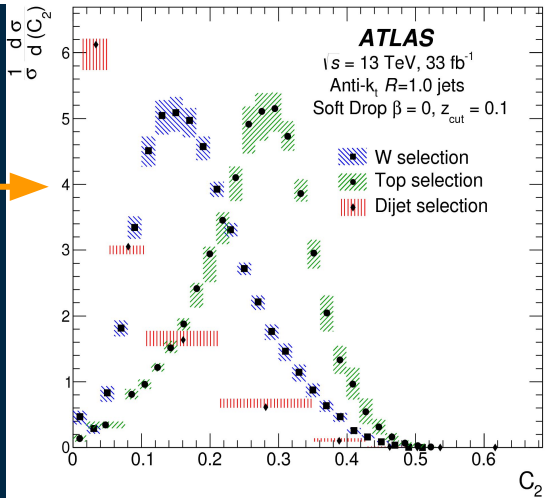
Energy correlation functions:
 ECF2:
 multi-prong has higher values

N-Subjettiness:
 τ_{21} : Lower values indicate more 2
 subjet like behaviour



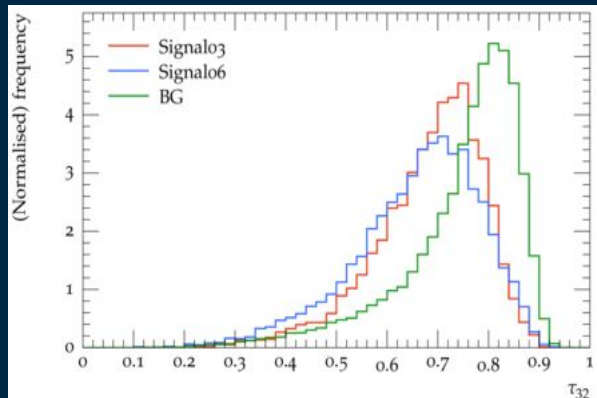
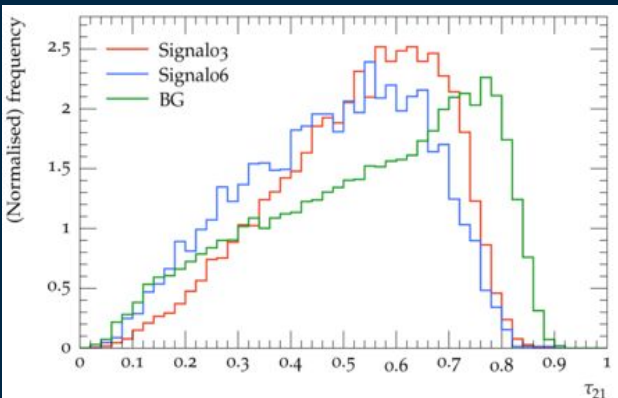
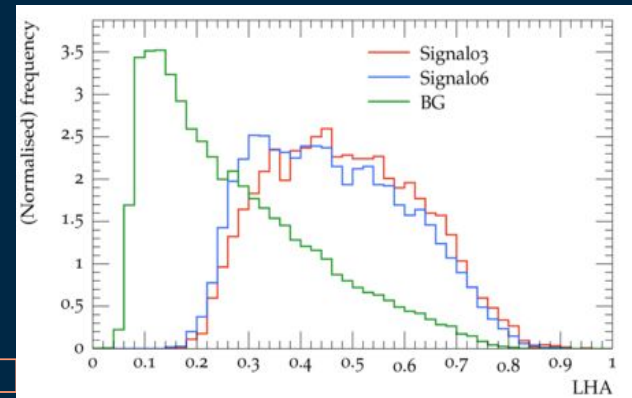
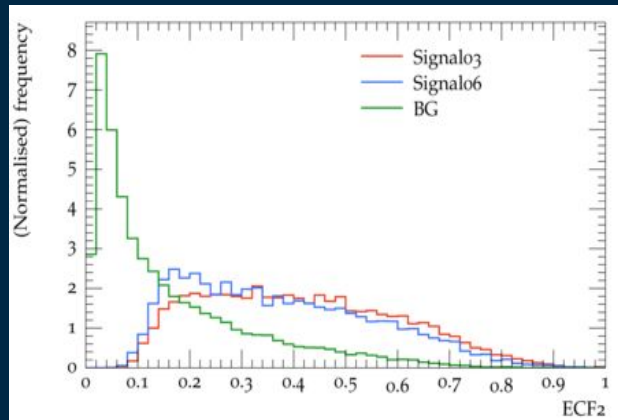
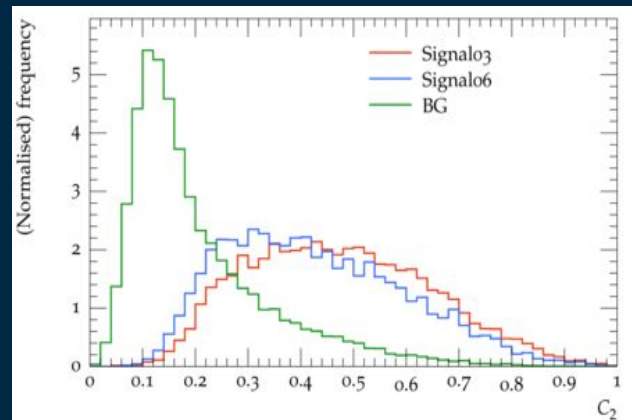
Energy correlation
 double ratios:
 C2: higher value has
 more subjets

[Link to paper](#)



Les Houches
 Angularity:
 higher value
 means hard
 radiations are
 more separated

Signal and Background comparison

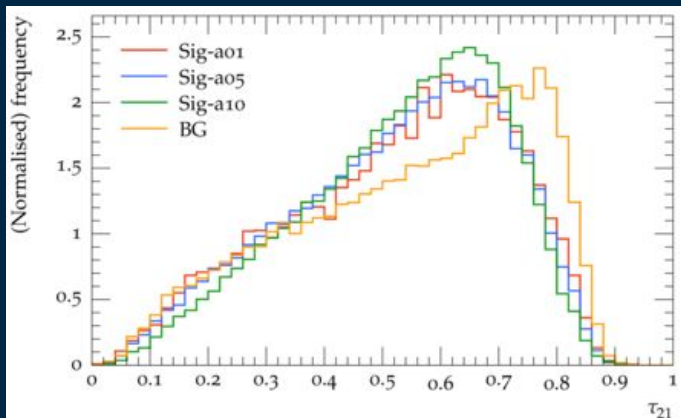
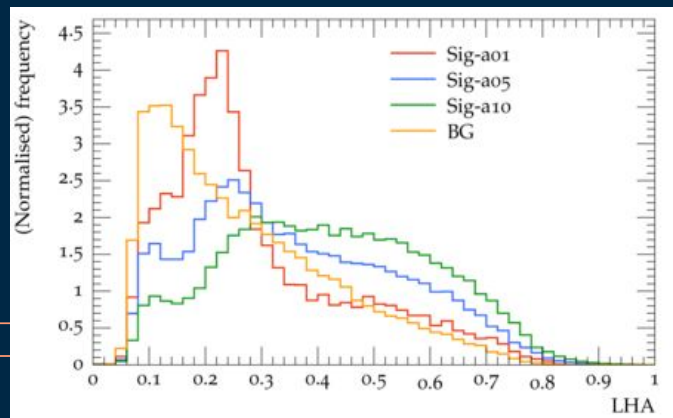
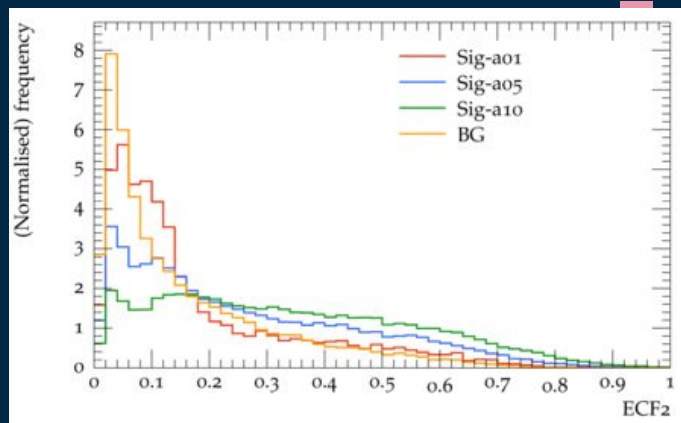
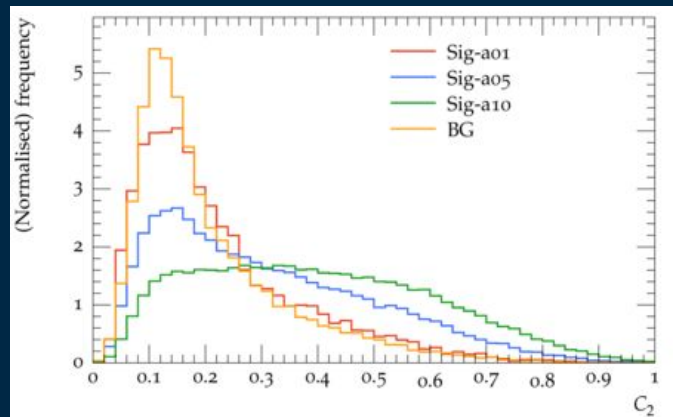


Choosing leading p_T jets for background, and jets closest to MET for signal

This is in p_T 400-600 bin (most signal), similar trend in p_T 800-1000 bin.

Same message from all plots, signal is more multi-pronged.

Study of model dependence



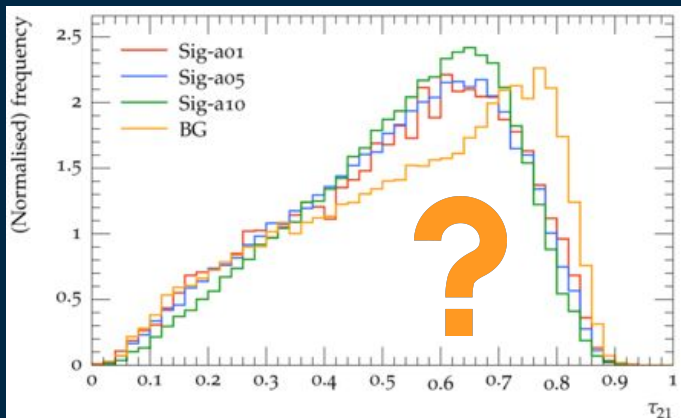
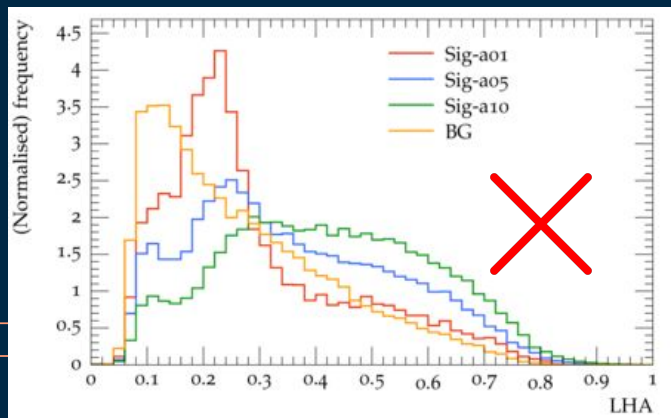
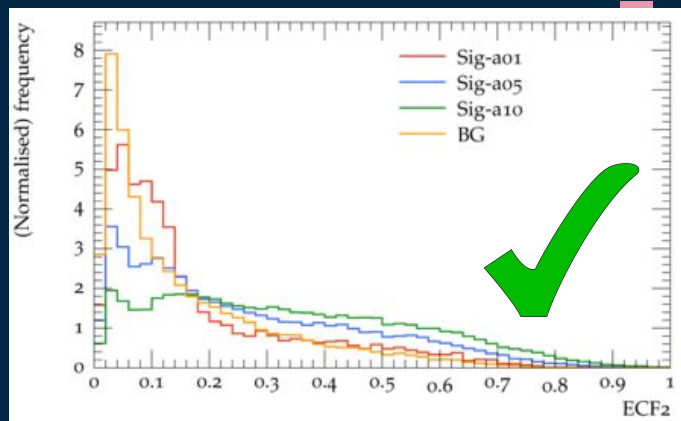
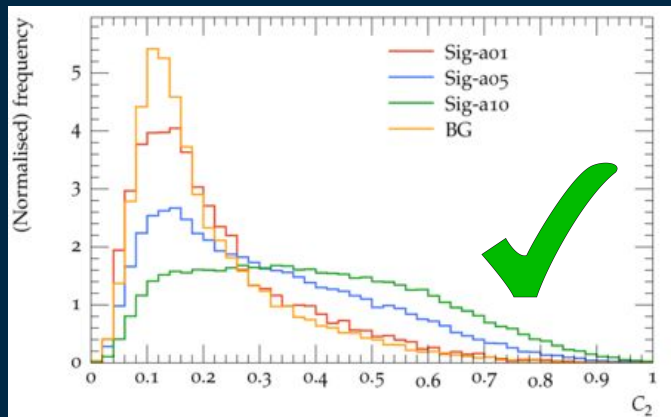
Lets see a representative case, which is similar to "darkjets" mentioned in S2:

Study $r_{inv} = 0$ signal comparison with bg, varying HV alphaFSR and ρ_T^{\min} .

Turns out ρ_T^{\min} does not have visible effect.

So only plots having $r_{inv} = 0$ signal comparison with background, varying alphaFSR are shown.

Study of model dependence



Use some variables to discriminate?

D2 behaves like C2

ECF3 behaves like ECF2

τ_{32} behaves like τ_{21} , but with more prominent differences

Worth noting that $\alpha_{FSR}=0.1$ is closest to BG, probably because that value is closest to the QCD alpha value

Attempt at understanding jet substructure of SVJ



Checks:

- Does decay from intermediate to final dark hadrons change anything?
- How does grooming affect jet substructure?
- What is effect of ISR and extra radiation on jet substructure?



For a detailed look at non-trivial theory systematics on jet substructure observables: See Also, Tim Cohen et al recent [paper](#)

Attempt at understanding jet substructure of SVJ



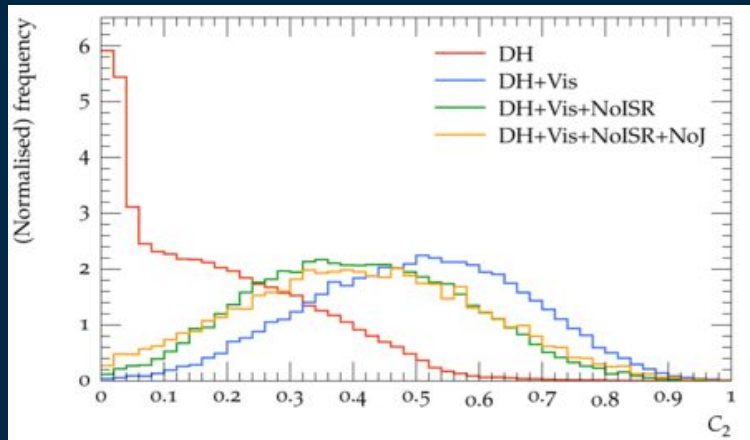
Checks:

In backup slides

- Does decay from intermediate to final dark hadrons change anything?
- How does grooming affect jet substructure?
- What is effect of ISR and extra radiation on jet substructure?
 - $r_{inv} = 1$, $\alpha_{FSR} = 0.1$ signal comparison
 - final dark hadrons clustered into jets - by themselves (DH),
 - with other visible hadrons (DH + Vis),
 - with other visible hadrons but no ISR (DH + Vis + no ISR),
 - with other visible hadrons but no extra jets in ME level, no ISR (DH + Vis + noISR + NoJ).

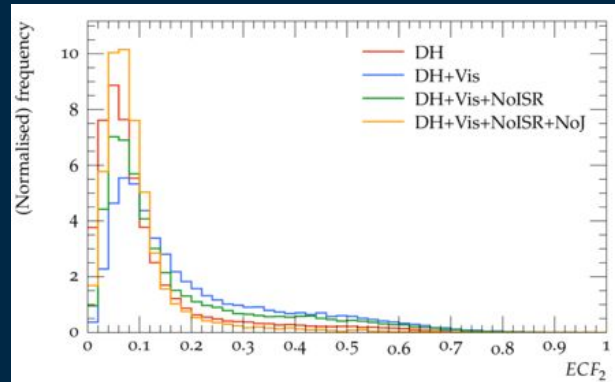
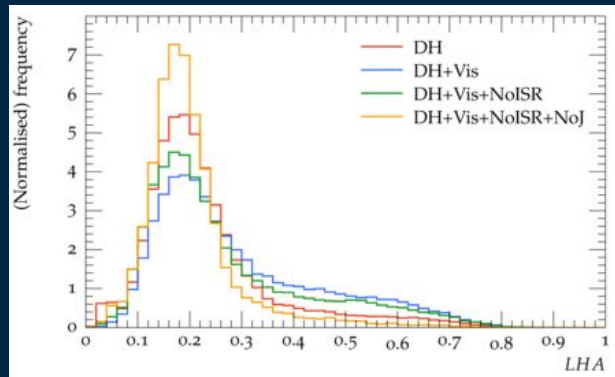
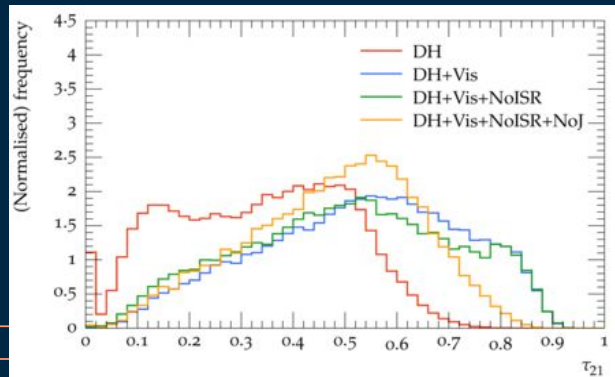


Substructure studies by directly clustering dark hadrons



Plots for $p_T = 400 - 600$ GeV

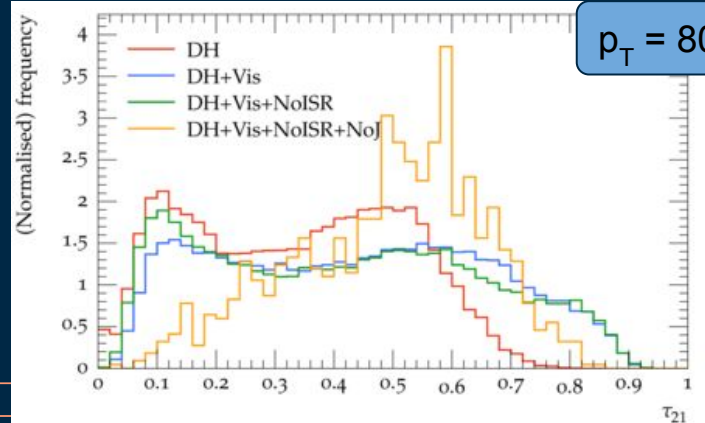
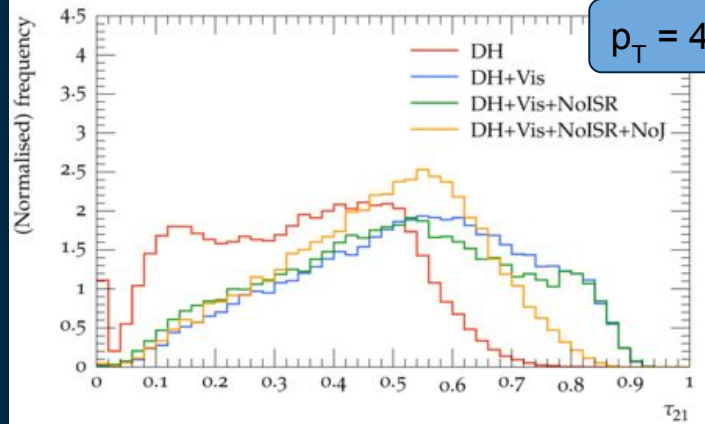
(similar trend for $p_T = 800 - 1000$ GeV)



Interpretations

- Adding Standard Model particles to clustering changes no. of sub jets massively, **mostly > 3 prong**.
- Lack of extra jets at ME level makes the signal jet less energetic, so the corresponding substructure pattern is wider.
- Taking off ME extra jets does not change pronginess but makes LHA closer to only dark hadrons scenario.
- **ISR** qualitatively has same effect as extra jets, but it **adds more activity to semi-visible jets** compared to ME extra jets, making slightly more multi-pronged. *Softer ISR particles spread more, not changing LHA.*

Icing on the cake: multiple populations!



τ_{21} shows multiple populations ($\alpha = 0.1$)

- Same effect when adding all SM hadrons.
- Absence of ISR does not affect, whereas absence of ME jets makes the 2 prong population weaker.
- Effect was also noticed when alpha values were lowered, and at higher p_T ranges, for $r_{inv} = 0$, as in S8.
- May indicate that smaller alpha values mean less radiation, and create 2-pronged jss, and also high pT means more collimated and more 2-pronged

Conclusions & Next Steps



Semi-visible jets tend to be more multi-pronged compared to light quark/gluon jets(!), leading to certain jet substructure variables having discriminatory power

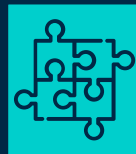


Mostly due to presence of only one dark shower module, so far, it is somewhat model dependent



However, our studies have shown that substructure is created by the interspersing of visible hadrons and ISR + extra jets with dark hadrons

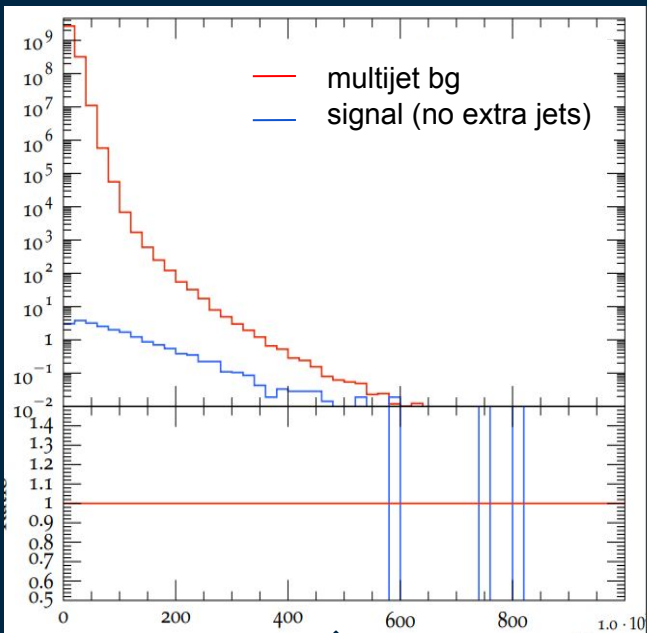
Yay!



Coming soon
at an arXiv
near you!

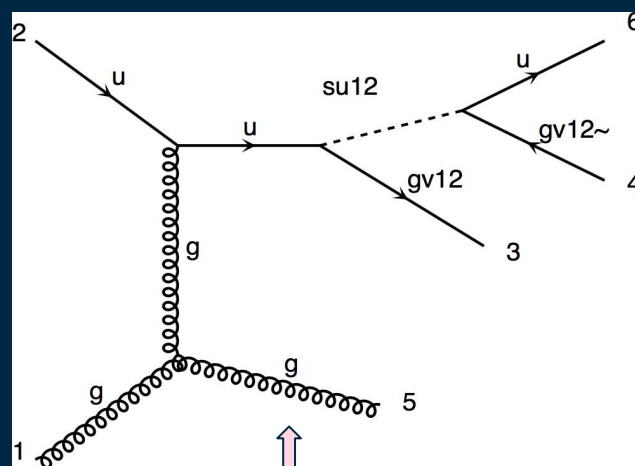
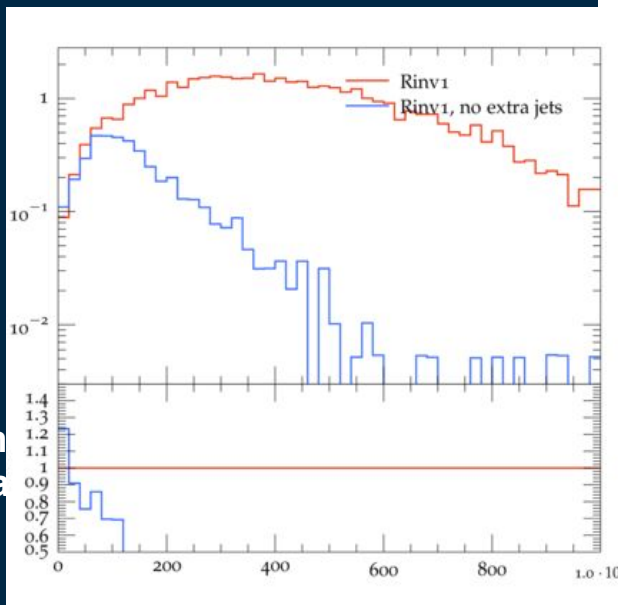
BACKUP SLIDES

- Why we need two extra jets?



Particle level MET plots for 2 scenarios:

1. signal (no extra jets) vs multijet background
2. $r_{inv} = 1$ (with and without extra jets)

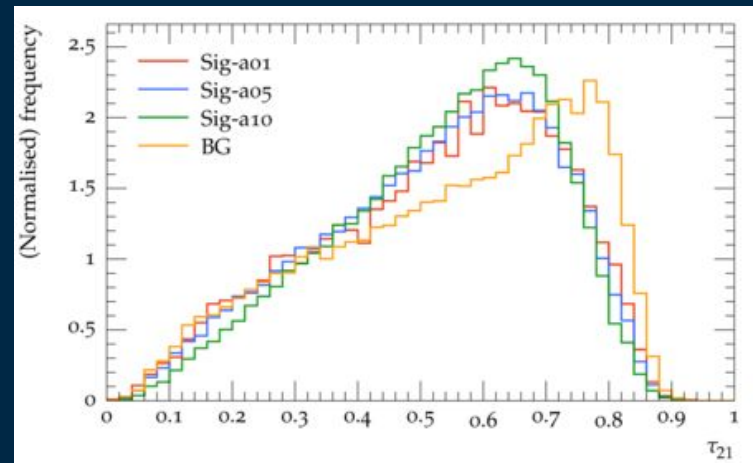


Extra jet multiplicity is due to twisted s-channel diagram contributions even when generating t-channel.

XS also increases on adding the 2 jets, which makes the search more powerful.

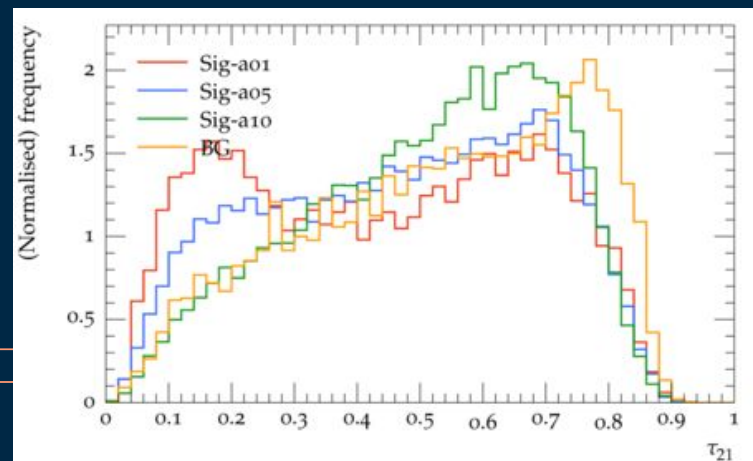
2 extra jets required to obtain a proper signal which is visible over the QCD background, unlike the no extra jet case (fig above).

Icing on the cake: multiple populations at high p_T !



τ_{21} in p_T range of 400 - 600 GeV (top)
800 - 1000 GeV (bottom) shows multiple
populations for $\alpha = 0.1$

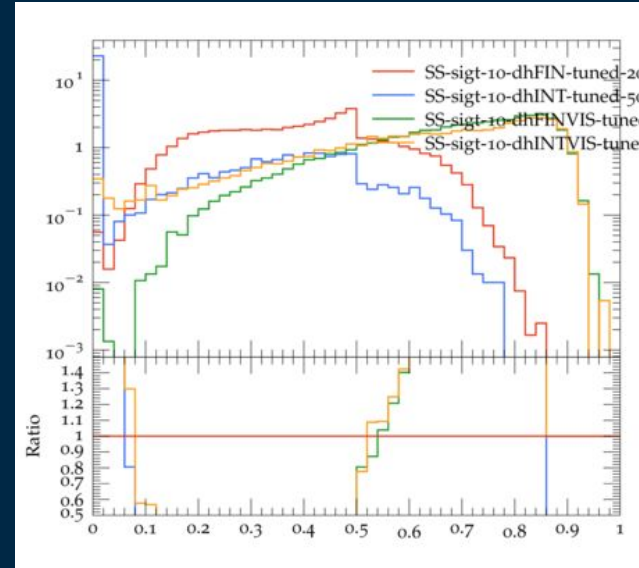
Indicates possibility of 2-pronged
structure (LHS) as well as non 2-pronged
structure (RHS)



Decays (shown: τ_{32})

Rather than clustering final DH in different combinations, same were repeated with intermediate DHs (INT), turning their decays off.

No visible difference except a slightly more flattish shape in lower values and slightly less max values for INT ones in τ .



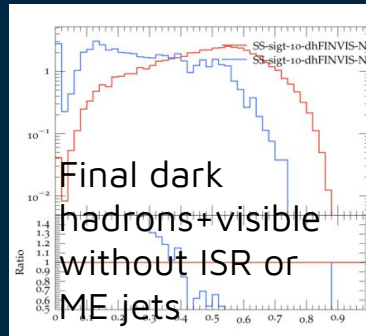
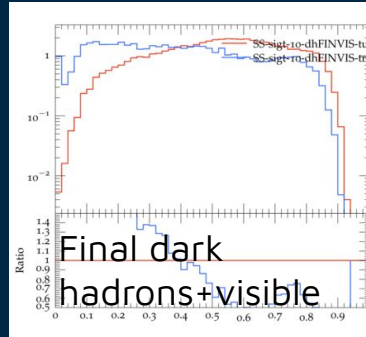
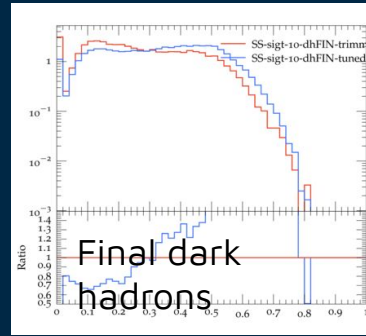
Red: Final dark hadrons clustered
Blue: Intermediate dark hadrons clustered
Green: Final dark hadrons+visible particles clustered
Yellow: Intermediate dark hadrons+visible particles clustered

Trimming (shown: τ_{21})

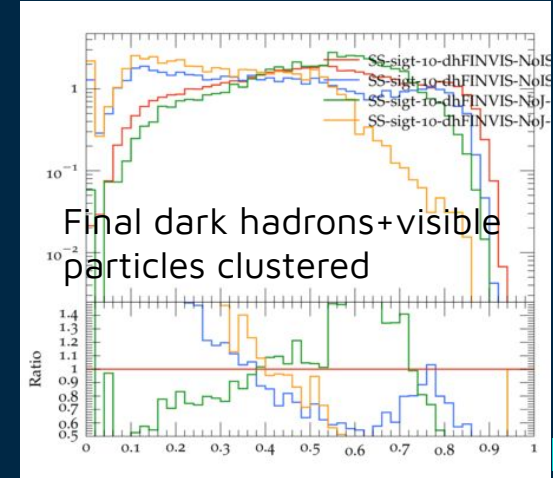
Trimming in general moves C2 to left, τ to the right. This is least pronounced for only DH case, more for DH+Vis and most pronounced for noISR+noextra jets cases.

However, no extra jet case shows the largest shift at higher values of τ , indicating ISR gets more affected by trimming. Less pronounced at C2.

p_T spectra does not change, as expected.



Red: Ungroomed
Blue: Trimmed



Red: No ISR, ungroomed
Blue: No ISR, trimmed
Green: No ME jets, ungroomed
Yellow: No ME jets, trimmed