Towards a Herwig dark shower + hadronization module and an attempt to better probe the dark sector

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Alongwith Andy Buckley, Deepak Kar, Andrzej Siodmok, Peter Richardson

Who am I?

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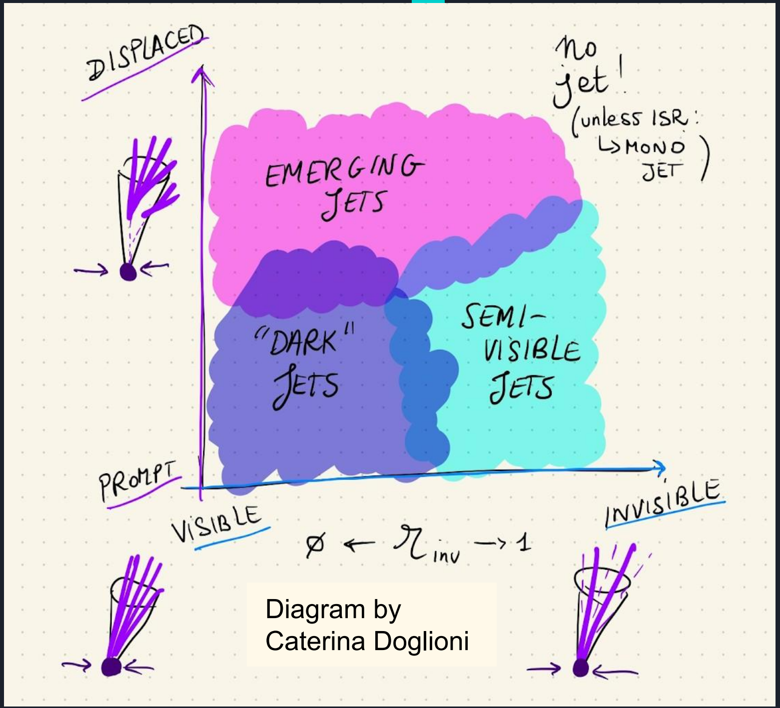
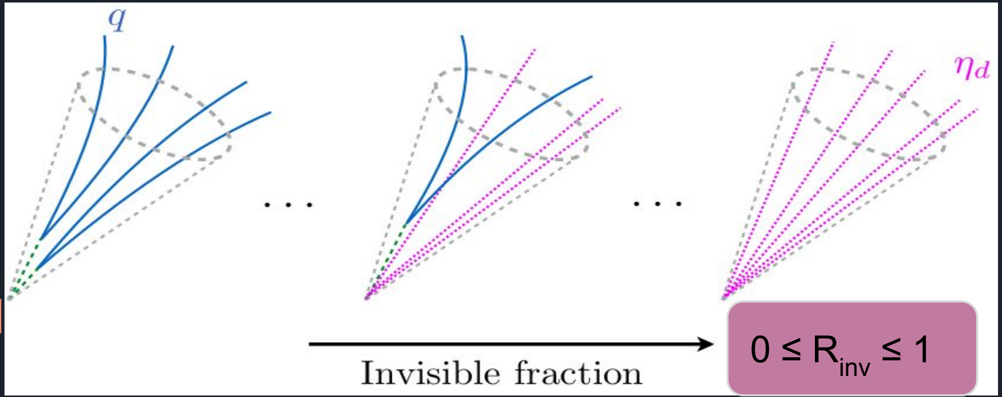
MCnet Shortie @ Glasgow University

Introduction

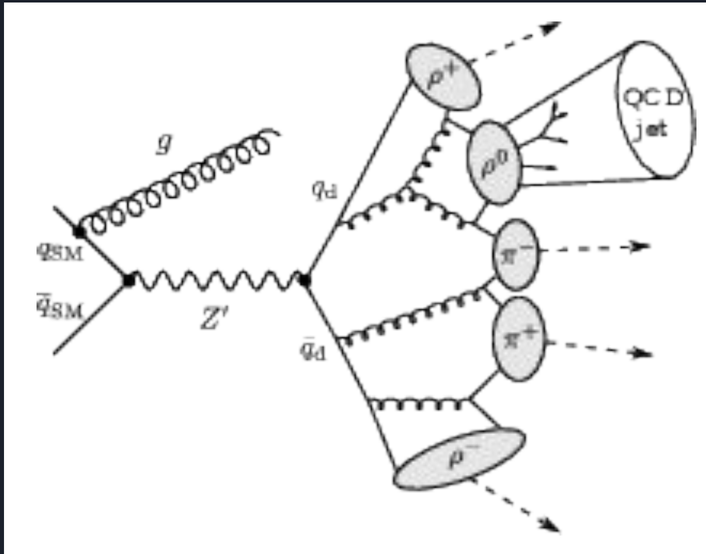
- Look at unusual topologies & hidden phase space corners
- Dark hadrons decay promptly in a QCD-like fashion partially back to visible sector **(semi-visible jets "SVJ")** Initial motivation
  - Showering using Pythia hidden valley module





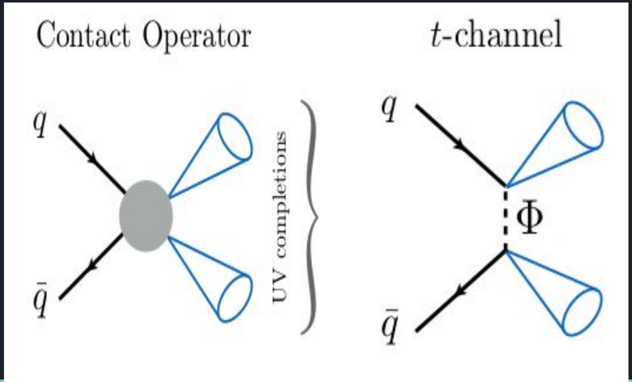
Based on the Paper:
LHC Searches for Dark Sector Showers : Tim Cohen et al [arXiv: 1707.05326]

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 → invisible



Model Parameters:

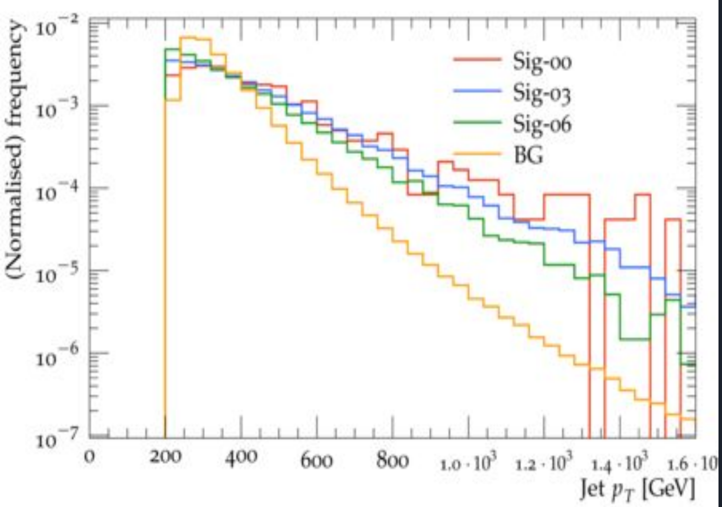
1. M_Φ = Mass of Scalar Bi - fundamental (mediator)
2. M_d = Mass of dark hadrons
3. r_{inv} = no. of stable dark hadrons/ no. of hadrons

Jet-substructure study

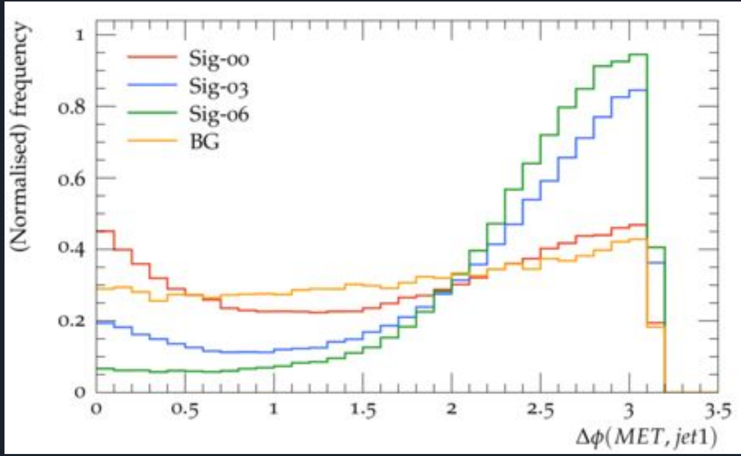
D.Kar & SS: https://arxiv.org/abs/2007.11597

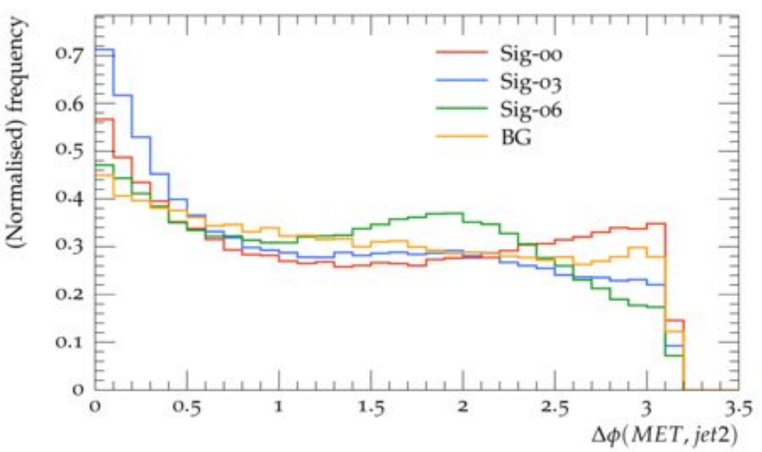
- Comparing jet substructure variables to see if SVJ substructure is different from light quark/gluon jets (BG). Do they behave more multi-pronged as opposed to mostly single prong?
- Comparison can be done in p_T bins or in m/p_T bins, picked the former, as there is no resonance.

t-channel makes it more challenging as no resonance peak



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

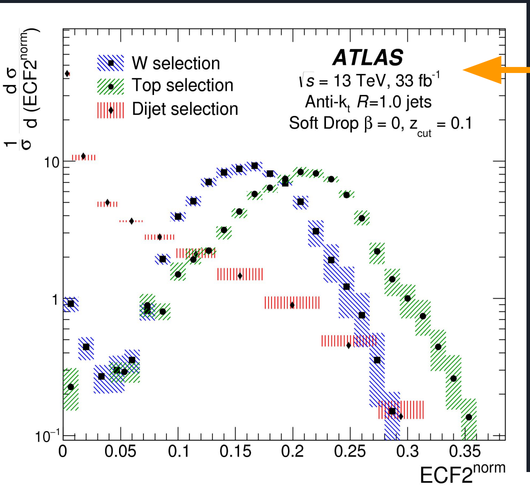




Signals (r_{inv} = 0, 0.3, 0.6) and multijet background generated using MG5 + Py8

Normally signals are generated with upto two extra jets!

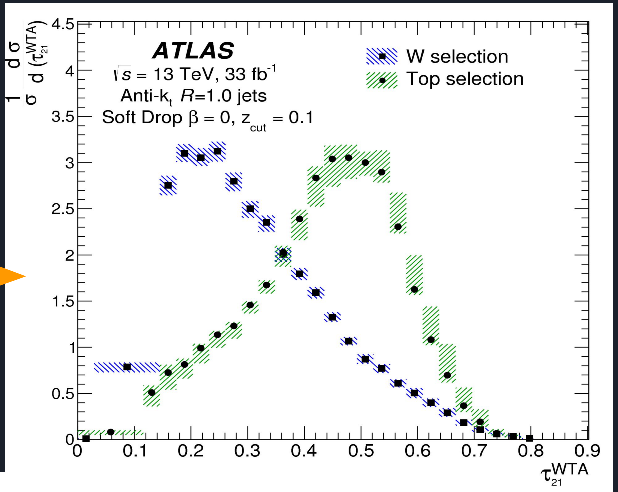
Plots from ATLAS to explain how the JSS variables behave



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

N-Subjettiness:

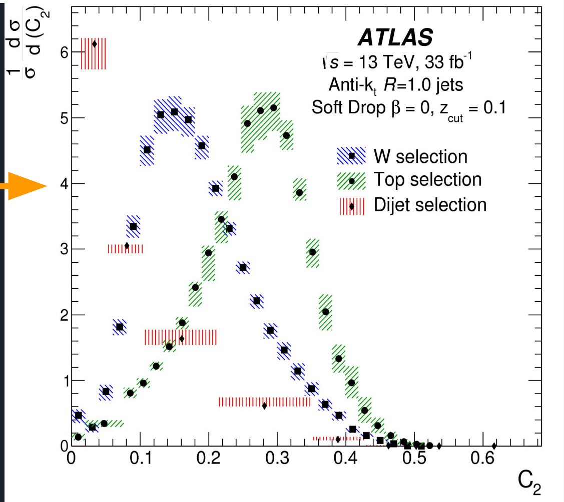
τ_{21}: Lower values indicate more 2 subjet like behaviour

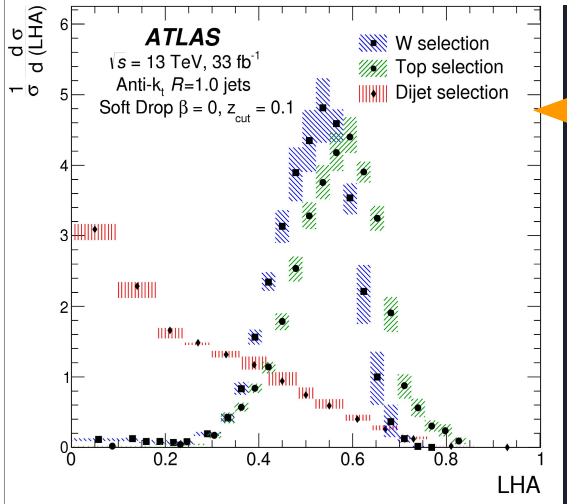


Energy correlation double ratios:

C2:higher value has more subjets

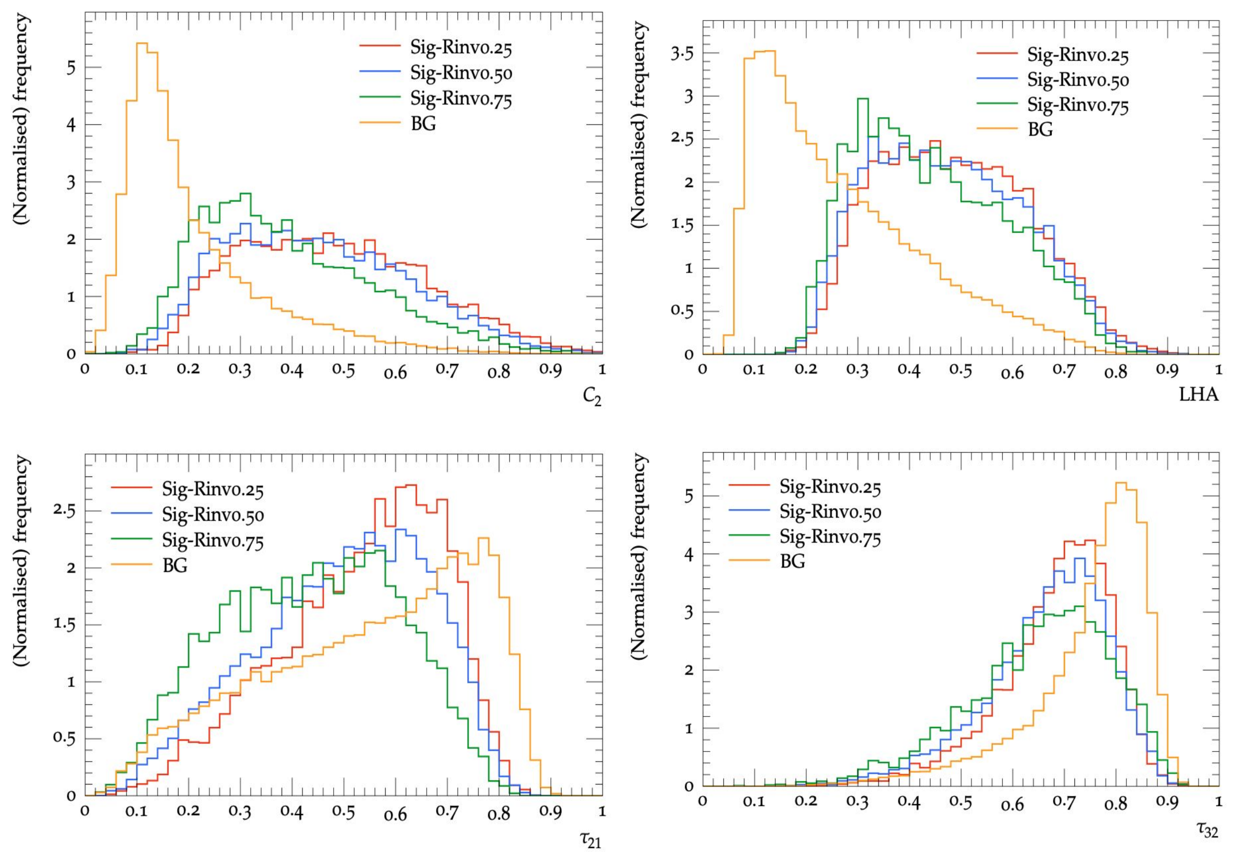
[Link to paper]





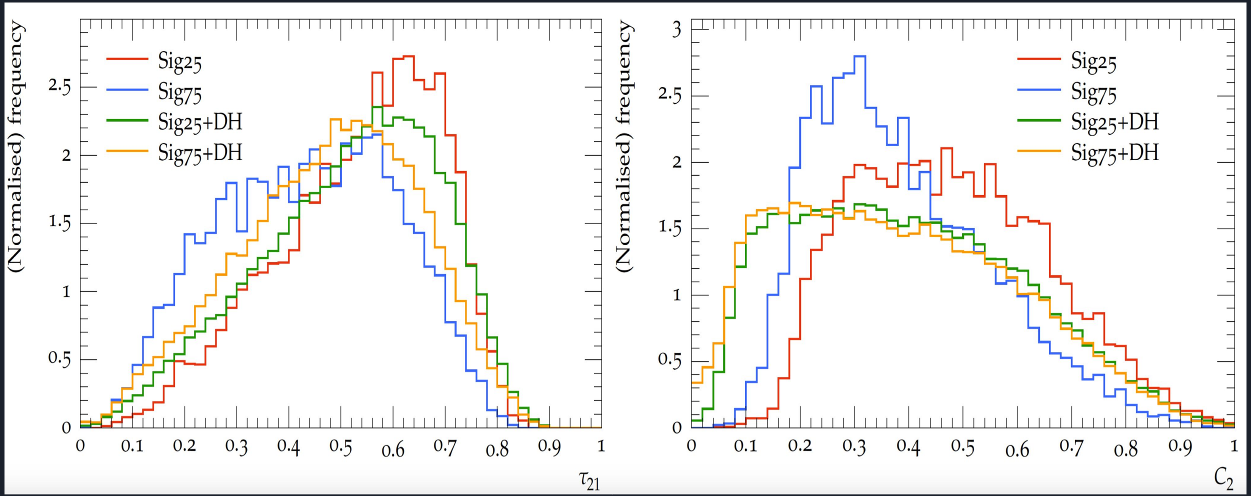
Les Houches Angularity: higher value means hard radiations are more separated

What effects are responsible for specific jet-substructure of semi-visible jets?



For finite r_{inv} values, when only the visible hadrons are clustered in jets, subtle substructure difference observed for different Rinv values.

What effects are responsible for specific jet-substructure of semi-visible jets?



If the final dark hadrons are also clustered in the jets ---> expect this difference to go away ----> the different amount of missing hadrons in each case presumably is responsible for the difference.

Conclusions:

1. The substructure becomes less two-pronged with visible and dark hadrons in them, and the absence of the dark hadrons create the two-pronged structure ---> The substructure is created by the interspersing of visible hadrons with dark hadrons.
2. Specific hidden valley parameter configurations can reduce the dark shower model dependent features of the signal jets.

However….

- Mostly due to presence of only one dark shower module, so far, all studies are somewhat model dependent
- Several other observables may be out there, that can help discriminate these unconventional jets from the standard q/g jets

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Necessity of an additional dark-shower module

Why Herwig?

- ➔ Herwig is using systematically different shower and hadronization models from Pythia
  - ◆ Herwig dark hadronization would naturally be cluster- rather than string-based, hence there really is a model difference.
- ➔ Helps to get a better estimate of theory associated uncertainties.
- ➔ Apart from the standard dark confinement scale, and the renormalisation scale multiplier in the shower, different hadronization procedure might also play a key role, and we suspect that the difference between cluster and string models could be similar to the individual physically feasible variations within either of them.

Preliminary plan for implementation of Herwig HV hadronisation module

- ➔ Start with dark mesons “only”
  - ◆ Masses comparable to QCD scale
- ➔ Have a separate dark hadronization prehandler, that mimics the SM hadronization
  - ◆ sans the fission, and other complicated machinery at play in the SM part
- ➔ This prehandler runs before the standard model hadronization handler

With a lot of help from Andrzej and Peter R (Thanks in advance!) 😀

Because of completely different dark-sector radiation & hadronization relating to Pythia, it will help to better estimate model uncertainties.

However....

- Mostly due to presence of only one dark shower module, so far, all studies are somewhat model dependent
- **Several other observables may be out there, that can help discriminate these unconventional jets from the standard q/g jets**

Energy - flow polynomials

- A complete linear basis for jet substructure

J. Thaler et al

https://arxiv.org/pdf/1712.07124.pdf

What are EFPs?

- Observables that are multiparticle energy correlators with specific angular structures which directly result from IRC safety

EFPs form a linear basis of all IRC-safe observables, making them suitable for a wide variety of jet substructure contexts where linear methods are applicable

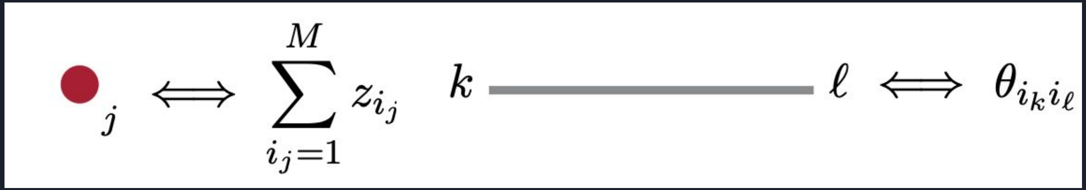
For a multigraph G with N vertices and edges (k, l) ∈ G, the corresponding EFP takes the form:

$$\text{EFP}_G = \sum_{i_1=1}^{M} \cdots \sum_{i_N=1}^{M} z_{i_1} \cdots z_{i_N} \prod_{(k,\ell)\in G} \theta_{i_k i_\ell}$$

where the jet consists of M particles, z_i is the energy fraction carried by particle i, and θ_{ij} is the angular distance between particles i and j.

Set of EFPs can be considered as the energy flow basis.

How to compute EFPs?



Each edge (k,l) in a multigraph is in one-to-one correspondence with a term θ in an angular monomial

Each vertex j in the multigraph corresponds to a factor of z and summation over i_j in the EFP

How to compute EFPs?

$$\Longleftrightarrow \sum_{i_j=1}^{M} z_{i_j}$$

$$\Longleftrightarrow \theta_{i_k i_\ell}$$

Each edge (k,l) in a multigraph is in one-to-one correspondence with a term θ in an angular monomial

Each vertex j in the multigraph corresponds to a factor of z and summation over i_j in the EFP

$$= \sum_{i_1=1}^{M} \sum_{i_2=1}^{M} z_{i_1} z_{i_2} \theta_{i_1 i_2}$$

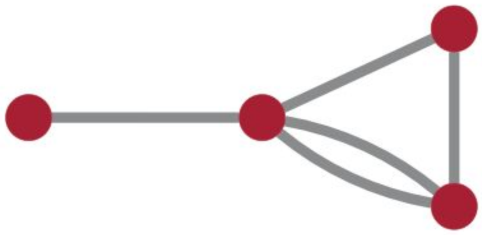
2 particles/constituents in a jet ---> 2 energy fractions, 1 angularity value ----> degree 1 polynomial

How to compute EFPs?

$$j \iff \sum_{i_j=1}^{M} z_{i_j} \qquad k \quad \ell \iff \theta_{i_k i_\ell}$$

Each edge (k,l) in a multigraph is in one-to-one correspondence with a term θ in an angular monomial

Each vertex j in the multigraph corresponds to a factor of z and summation over i_j in the EFP



$$= \sum_{i_1=1}^{M} \sum_{i_2=1}^{M} \sum_{i_3=1}^{M} \sum_{i_4=1}^{M} z_{i_1} z_{i_2} z_{i_3} z_{i_4} \theta_{i_1 i_2} \theta_{i_2 i_3} \theta^2_{i_2 i_4} \theta_{i_3 i_4}$$

4 particles/constituents in a jet ---> 4 energy fractions, 5 angularity values ----> degree 5 polynomial

Because the EFP basis is infinite, a suitable organization and truncation scheme is necessary to use the basis in practice.

How to compute EFPs?

	d	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
N	**2**	1	1	1	1	1	1	1	1	1	1
	3		1	2	3	4	6	7	9	11	13
	4			2	5	11	22	37	61	95	141
	5				3	11	34	85	193	396	771
	6					6	29	110	348	969	2 445
	7						11	70	339	1 318	4 457
	8							23	185	1 067	4 940
	9								47	479	3 294
	10									106	1 279
	11										235

Several combinations for diagrams possible

How to compute EFPs?

N \ d	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
2	1	1	1	1	1	1	1	1	1	1
3		1	2	3	4	6	7	9	11	13
4			2	5	11	22	37	61	95	141
5				3	11	34	85	193	396	771
6					6	29	110	348	969	2 445
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Several combinations for diagrams possible

Restricting ourselves to this regime…

The linked paper discusses in great detail how different EFP combinations lead to well-known jss observables

What we ideally want to achieve with EFPs?

- Implement EFPs in Rivet and see if any particular combination of EFPs helps to distinguish between standard q/g jets and more unconventional jets
    - Leading to a new jet-substructure observable for dark shower discrimination (?)
- Very preliminary setup working (computing EFP multigraphs till $N = 3$, $d = N - 1, N, N + 1$)

```
r (unsigned i = 0; i < constituents.size(); i++) {
  for (unsigned j = 0; j < constituents.size(); j++) {
    for (unsigned k = 0; k < constituents.size(); k++) {
      for (unsigned l = 0; l < constituents.size(); l++) {
        if (i==j || j==k || k==i || i==l || j==l || k==l) continue;

        EFP_d3_arrow =  (constituents[i].pt()/ptJ)*(constituents[j].pt()/ptJ)*(constituents[k].pt()/ptJ)*(constituents[l].pt()/ptJ)*
        deltaR(constituents[i].eta(),constituents[j].eta(),constituents[i].phi(),constituents[j].phi())*
        deltaR(constituents[i].eta(),constituents[k].eta(),constituents[i].phi(),constituents[k].phi())*
        deltaR(constituents[i].eta(),constituents[l].eta(),constituents[i].phi(),constituents[l].phi());

        EFP_d3_bow = (constituents[i].pt()/ptJ)*(constituents[j].pt()/ptJ)*(constituents[k].pt()/ptJ)*(constituents[l].pt()/ptJ)*
        deltaR(constituents[i].eta(),constituents[j].eta(),constituents[i].phi(),constituents[j].phi())*
        deltaR(constituents[i].eta(),constituents[k].eta(),constituents[i].phi(),constituents[k].phi())*
        deltaR(constituents[k].eta(),constituents[l].eta(),constituents[k].phi(),constituents[l].phi());
```

- Hopefully more substantial results to be shown in the next MCnet meeting :-)