# Dark Showers and Hadronisation in Herwig

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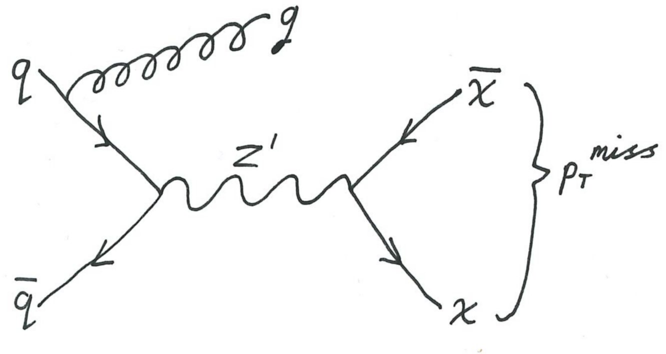
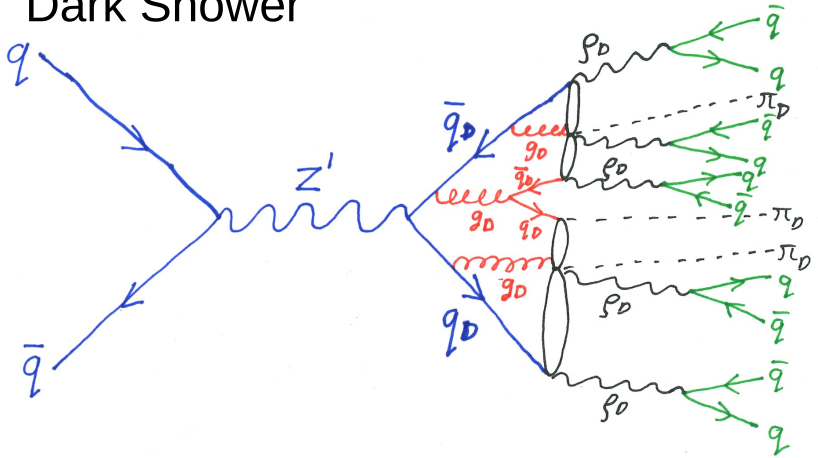
# Dark Showers

- One of the main LHC goals is to search for "WIMP" dark matter
  - However no significant evidence from traditional missing transverse momentum ($p_T^{miss}$) searches
- Dark sector could be much richer
  - More particles
  - Forces between dark particles
- If new force is confining, it would lead to "dark shower" and hadronisation

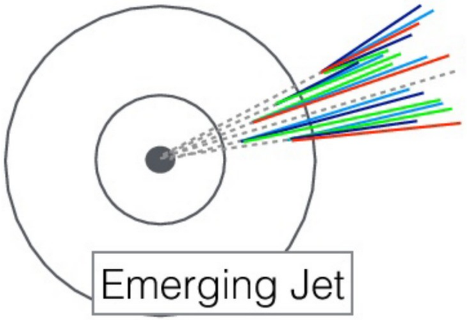
Traditional "mono jet" DM production

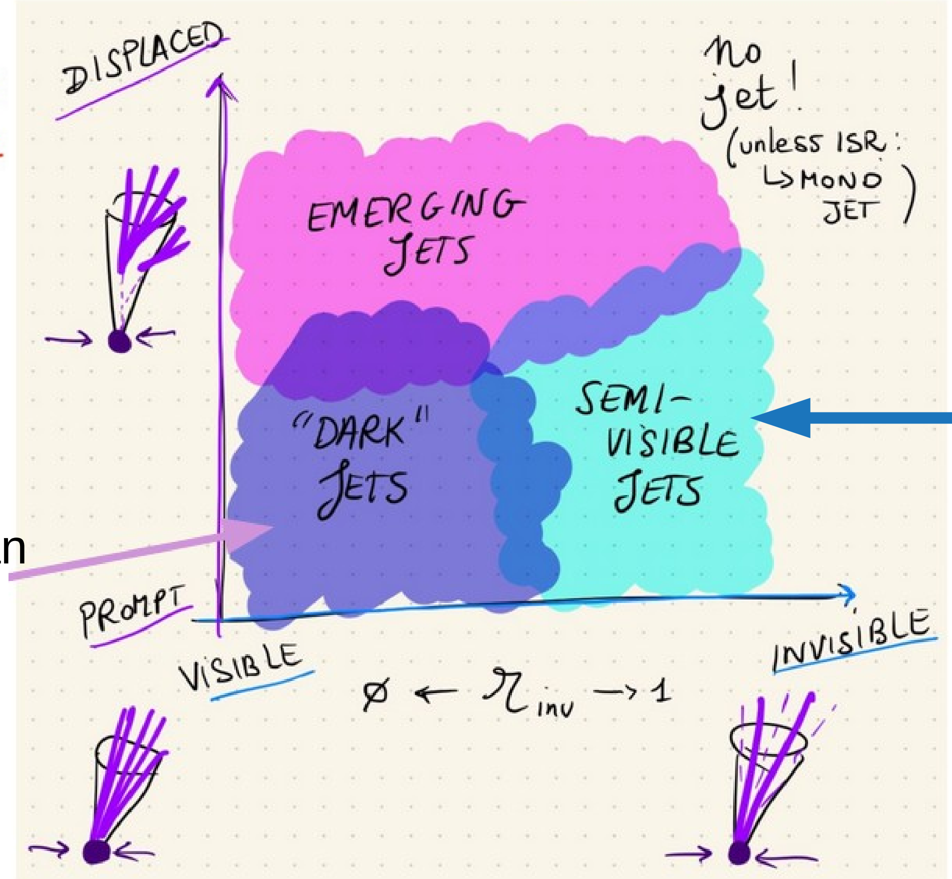


Dark Shower



# Signatures



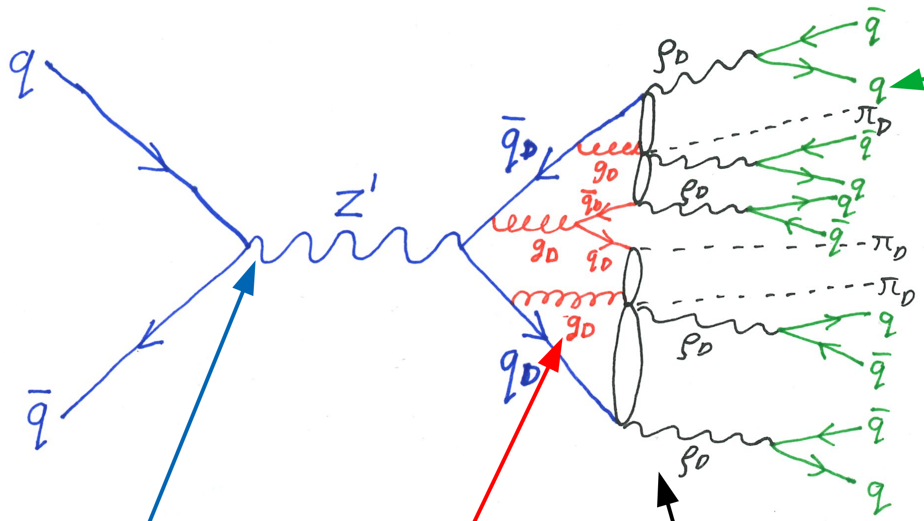




$p_T^{miss}$ aligned with jets, jet substructure also useful

Little $p_T^{miss}$, but can be distinguished through jet substructure

# Generating Dark Showers

Involves Physics at a range of scales:




Decays:
2 body phase space (trivial)
3 body perturbative (calculable)

- So far, only implemented in Pythia
- Herwig uses different shower and hadronisation models
- Can act as a useful complement

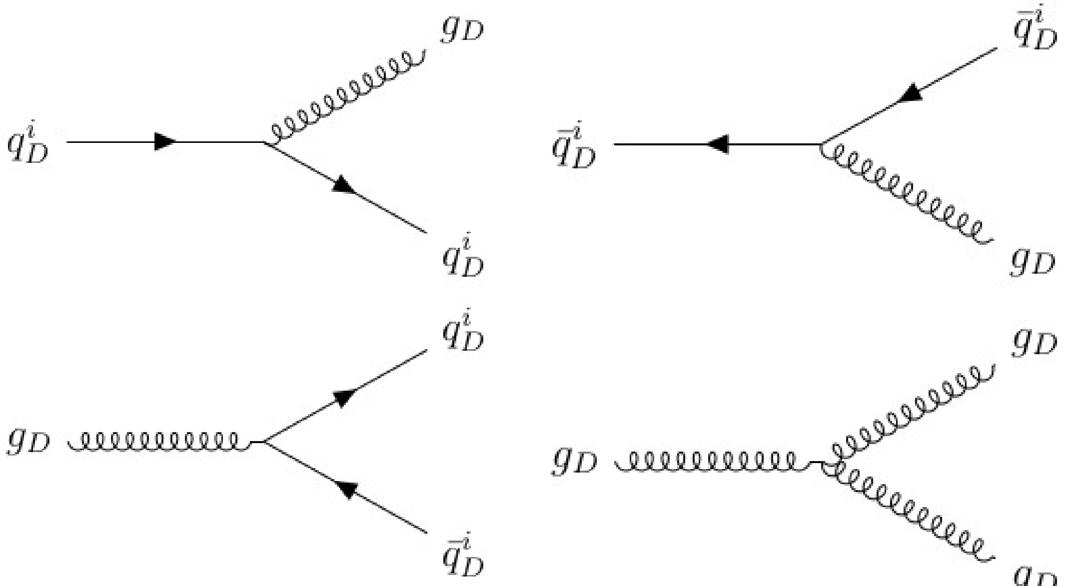
Hard Process:
Perturbative, well known

Parton Shower:
Perturbative, calculable

Hadronisation:
Non-perturbative semi-empirical models – challenging!

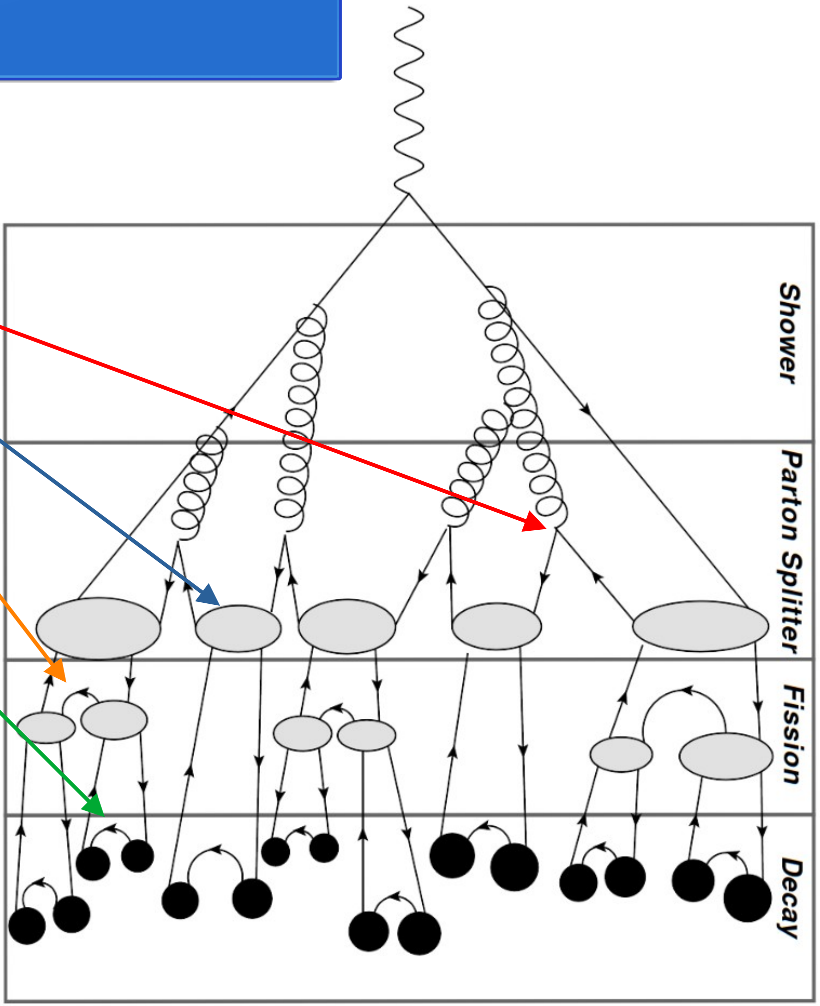
# Dark Parton Shower

- Model assumes a structure similar to QCD, with a number of “dark quarks”, $q^i_D$, and “dark gluons”, $g_D$, mediating the force between them
- Now implemented based on BSM extension of Herwig angular ordered parton shower
- Parameterise $\alpha_D$ by $\Lambda_D$, stay in QCD-like regime - $N_F/N_C<2$



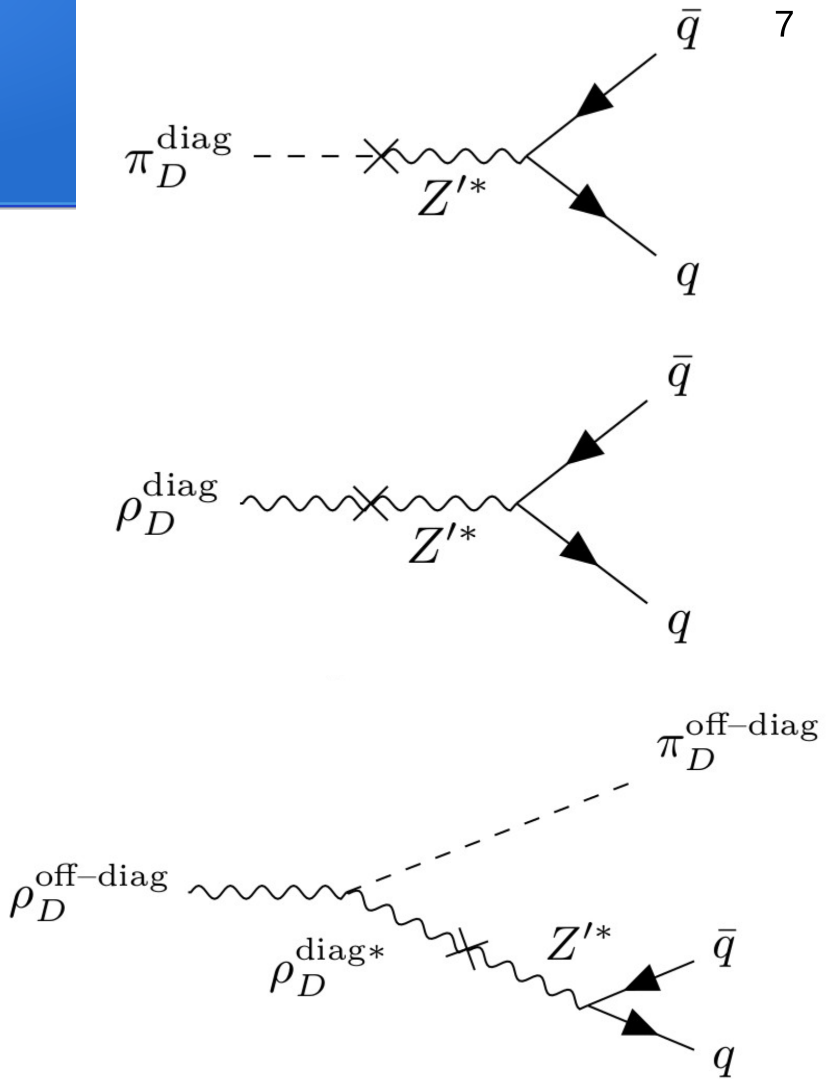
# Cluster Hadronisation Model

- Uses the cluster hadronisation model:
  - Gluons are split into $q\bar{q}$ pairs
  - Colour connected $q\bar{q}$ pairs form clusters (representing heavy pseudo-hadrons)
  - Very heavy clusters decay by springing $q\bar{q}$ pair from vacuum
  - Clusters decay to two hadrons according to phase space and number of available spin-states
- So far have only implemented dark mesons
- Depends on tunable parameters
  - Must be set based on SM values or intuition



# Dark Decays

- Unstable dark hadrons decay to SM quarks (which undergo a further parton shower and hadronise)
- Implemented using Darkonium decayer
  - Inspired by Quarkonium decayer, has correct colour connections for three body decays
  - Plan to add phase space dependance for 3 body decays in a future release



# Benchmark Model

Consider two broad scenarios (A and B):

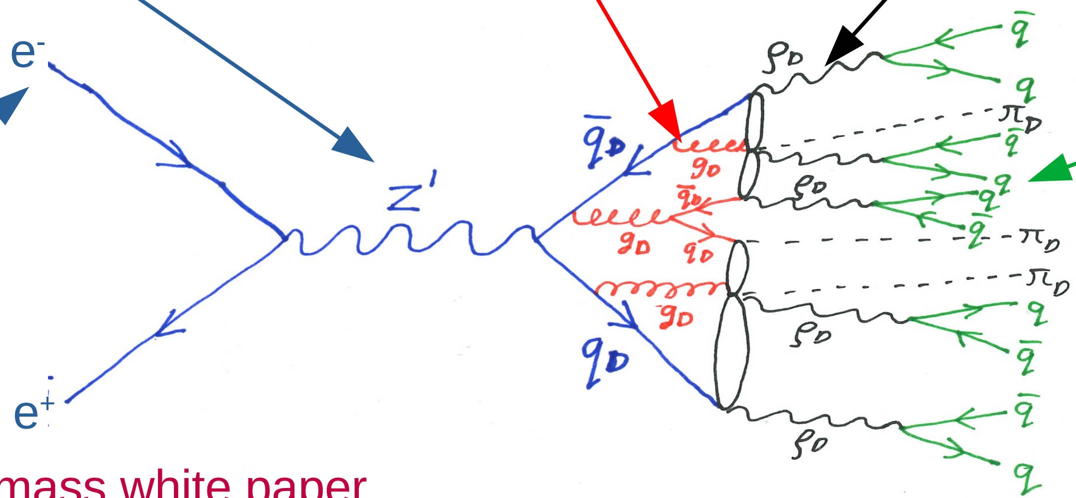
Mass degenerate dark quarks
Scenario A: $N_f$=3, $\Lambda_D \in$ [4, 10, 30] GeV
Scenario B: $N_f$=4, $\Lambda_D \in$ [1, 10] GeV

Need to select $\pi_D/\Lambda_D$, other masses from lattice

Scenario A: $\pi_D/\Lambda_D$=0.6
=> $m_{\rho D} > 2m_{\pi D}$
Scenario B: $\pi_D/\Lambda_D$=1.7
=> $m_{\rho D} < 2m_{\pi D}$

1 TeV Z' mediator

Start from $e^+e^-$ to have clean initial state




Scenario A: $\rho_D \rightarrow \pi_D\pi_D$, $\pi_D^{diag} \rightarrow q\bar{q}$ (heaviest available SM quark), off-diagonal $\pi_D$ stable

Scenario B: $\rho_D^{diag} \rightarrow q\bar{q}$, $\rho_D^{non\text{-}diag} \rightarrow \pi_D q\bar{q}$ (all available SM quarks), all $\pi_D$ stable

Based on Snowmass white paper
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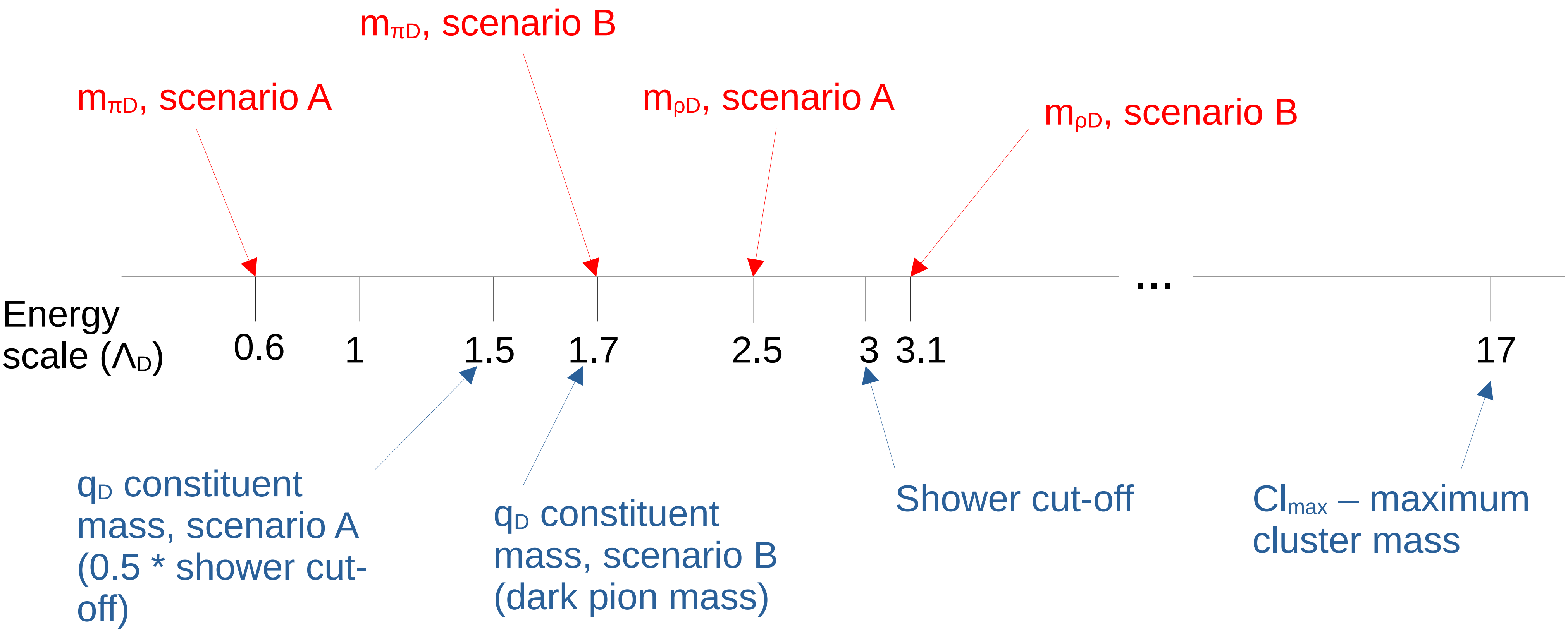
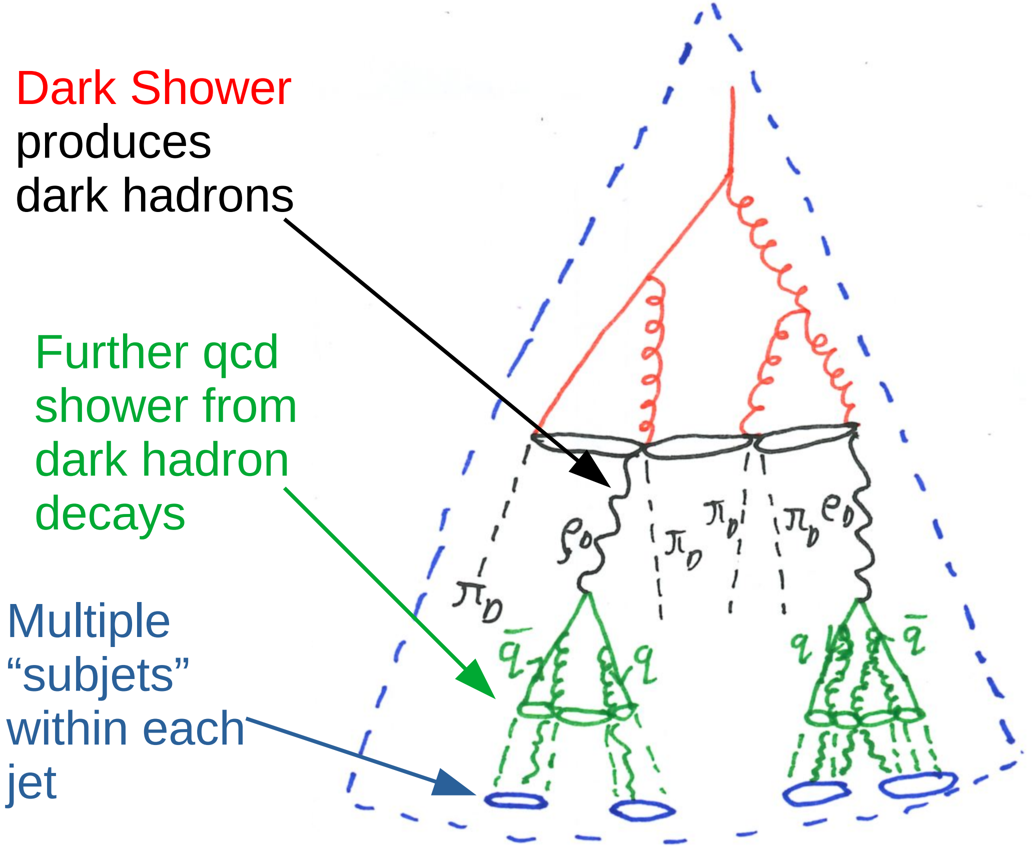
# Scale Hierarchies



# Jet Substructure

- Jets from dark showers can appear very different to SM QCD jets
  - Multiple “subjets”
- Can use variables sensitive to angular structures within a jet to search for these models
- Sensitive to details of dark shower and hadronisation

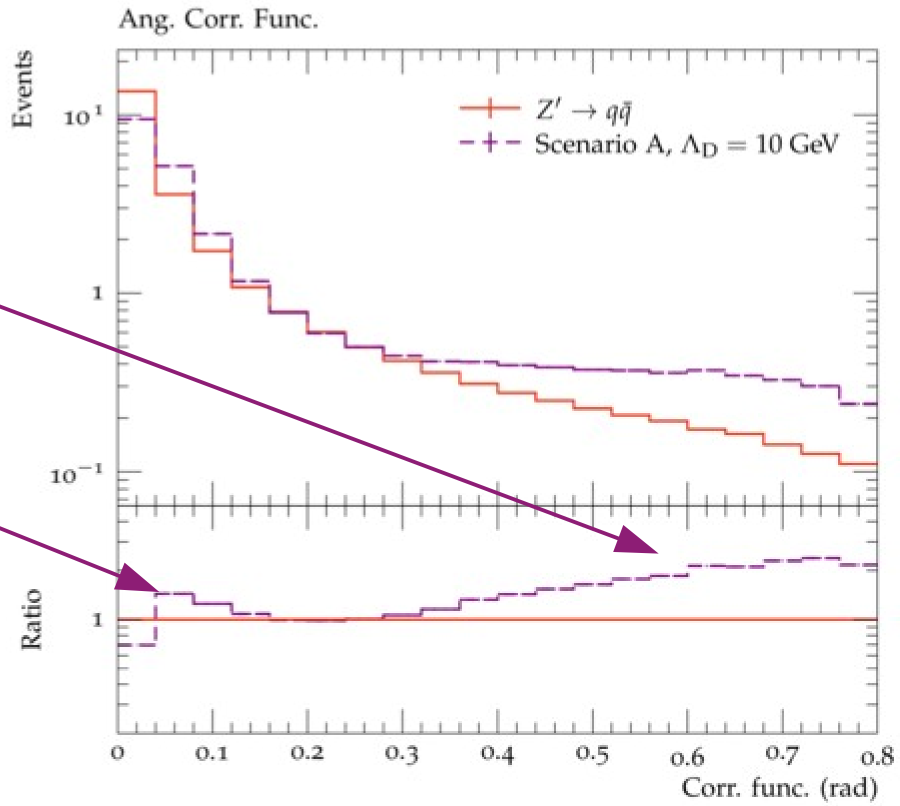


# Correlation Functions

- Plot angular distance between each pair of particles in the jets, weighted by energy of the particles
- Compare to production of SM quarks by same mediator

Excess at wide angles – distance between dark hadrons

Excess at small angles – distance between decay products of a single dark hadron

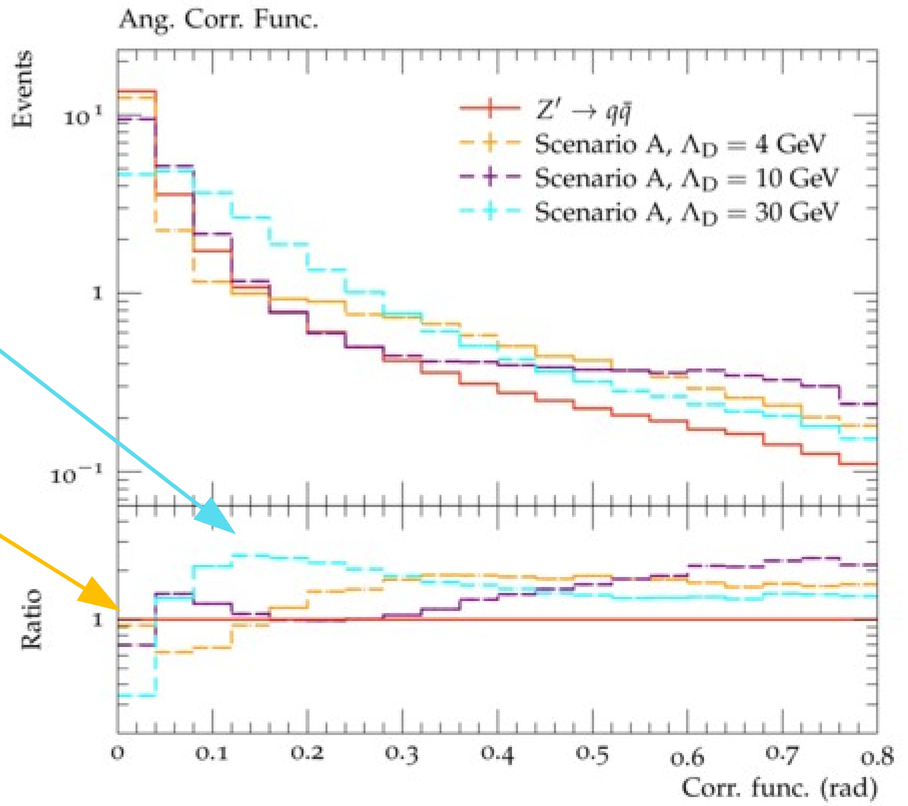


# Correlation Functions

- Lower $\Lambda_D$ shifts spectrum to smaller angles as dark hadrons are lighter and more boosted
- Overall difference to SM decreases as $\Lambda_D$ decreases since dark shower becomes more similar to QCD

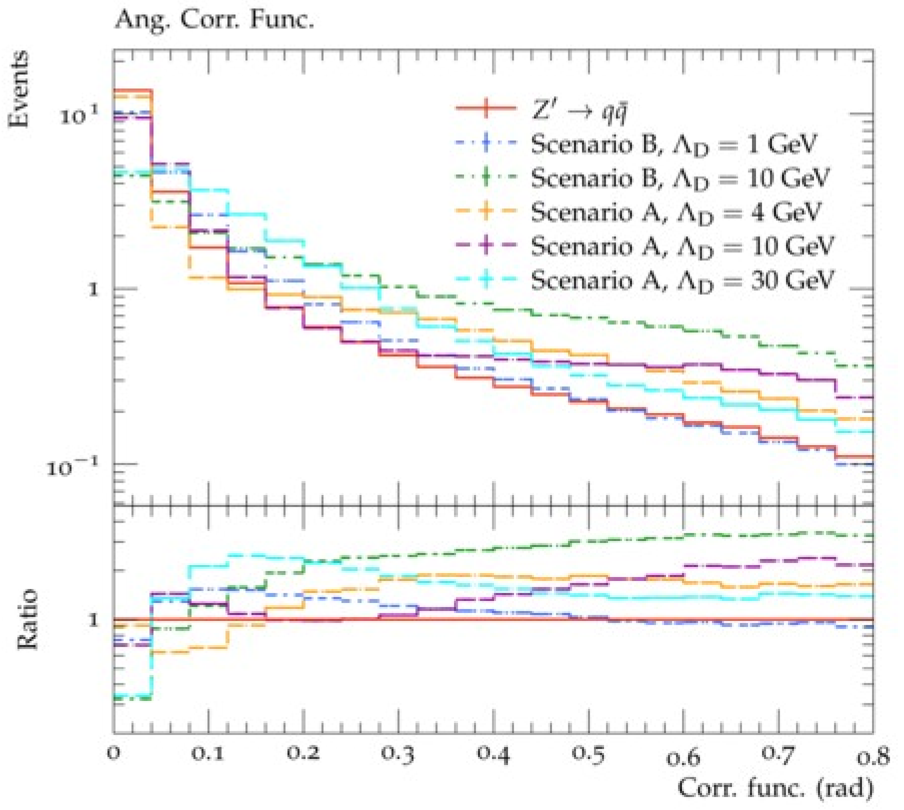
Only first peak visible inside jet for $\Lambda_D$=10 GeV

First peak for $\Lambda_D$=4 GeV only visible at very small angles



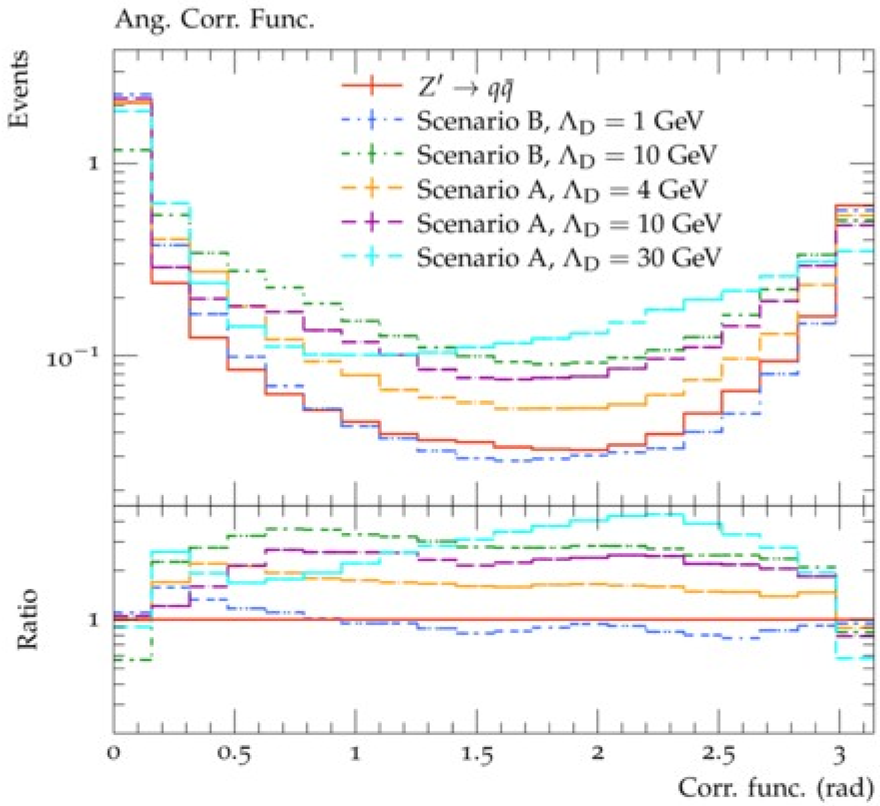
# Correlation Functions

- No visible two-peak structure for Scenario B
- Decaying dark hadrons much heavier ($\rho_D/\Lambda_D$=3.18 vs. $\pi_D/\Lambda_D$=0.6 for scenario A), so overlaps with second peak



# Correlations across Event

- Can also look at correlations across entire events
- Dark showers tend to have more isotropic topologies than QCD, due to:
  - Higher $\Lambda_D$ giving more wide-angle emissions
  - More cluster fissioning
  - Parts of event decaying invisibly

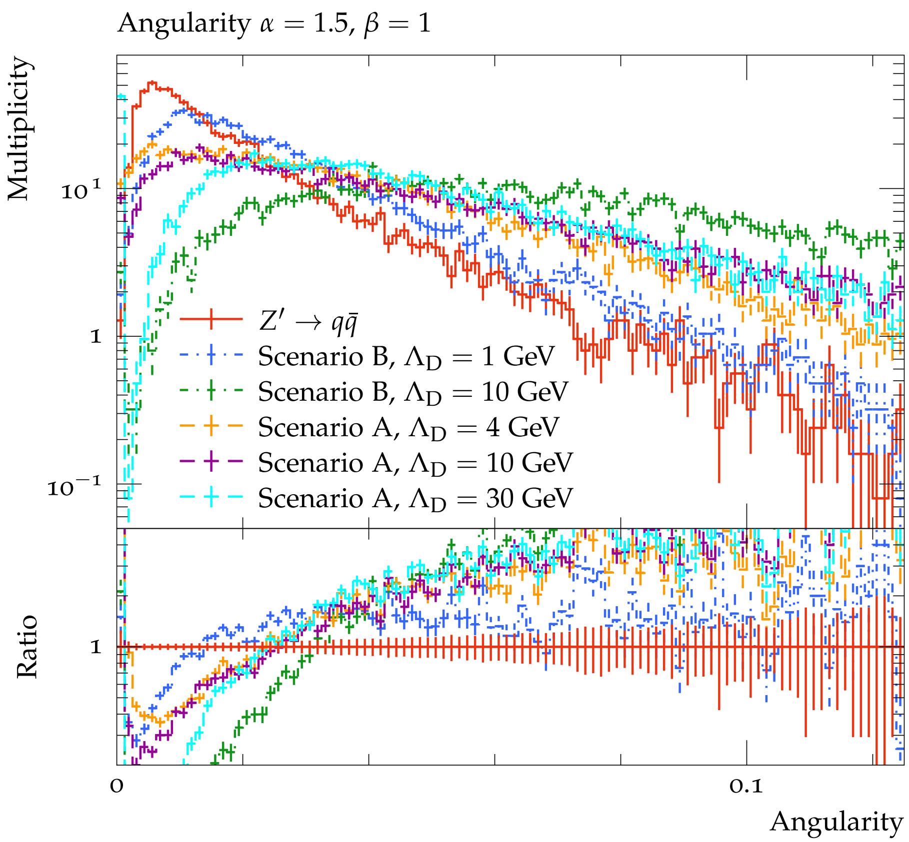


# Angularities

- Angularities also show discriminating power:

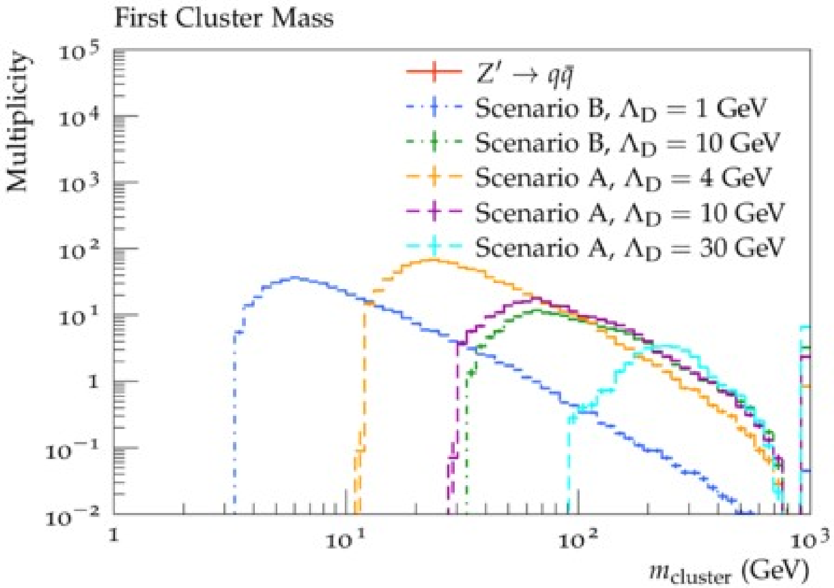
$$\sum_{i \in jet} \left( \frac{E_i}{E_{Tot}} \right)^{\beta} \left( 2\sqrt{1 - cos\theta_i} \right)^{\alpha}$$

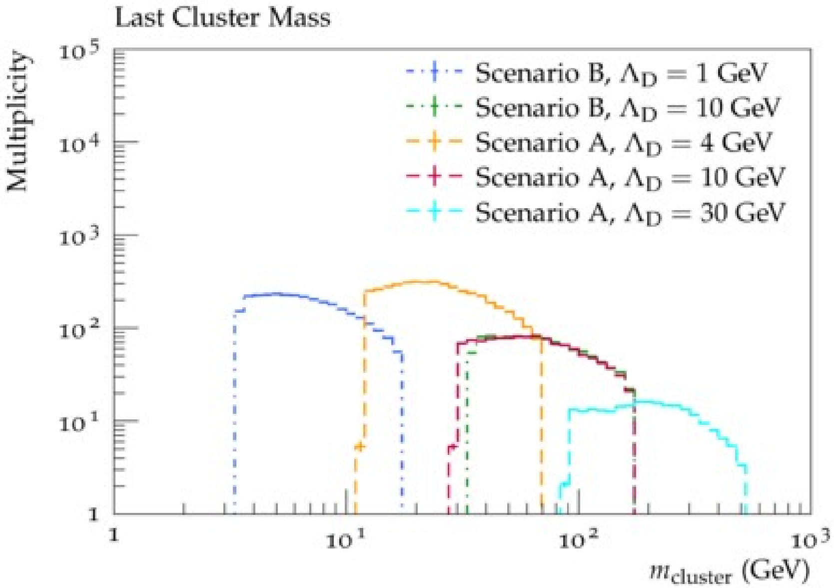
- IRC safe for β=1
- Varying α can probe different angular regions within jets
- Not as easy to observe different features, but provide per-event observable



# Hadronisation Parameters

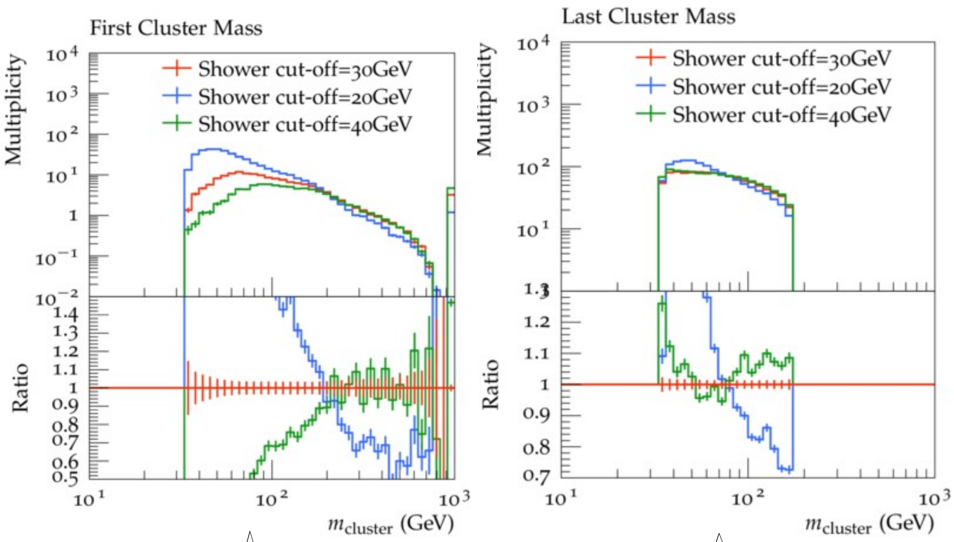
- Numerous parameters describing different aspects of hadronisation
- Impact of these parameters should be investigated for both final state and intermediate distributions (e.g. cluster masses)
- Studies performed for Scenario B, $\Lambda_D$=10 GeV
  - For scenario B hadronisation also determines visible decay fraction, since only $\rho_D$ decay

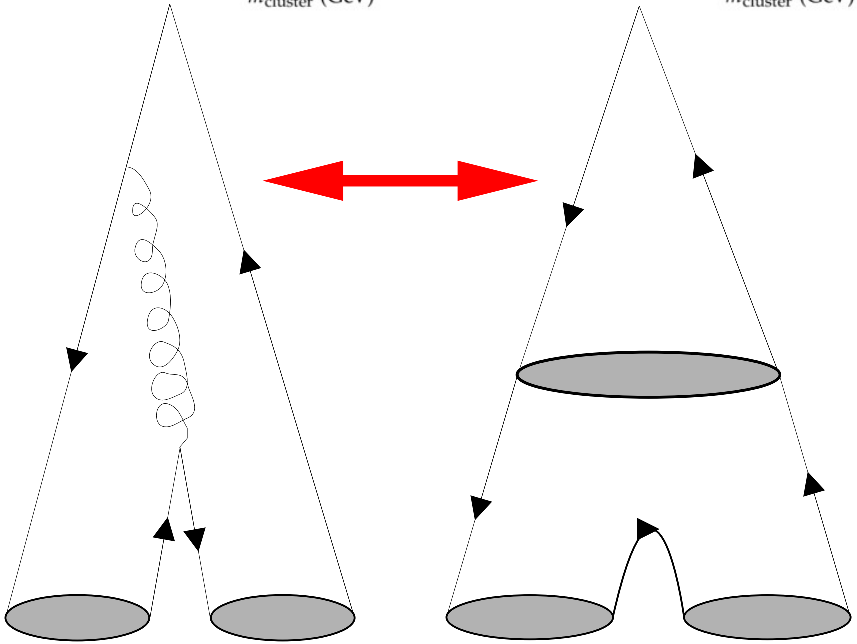


# Shower Cut-Off

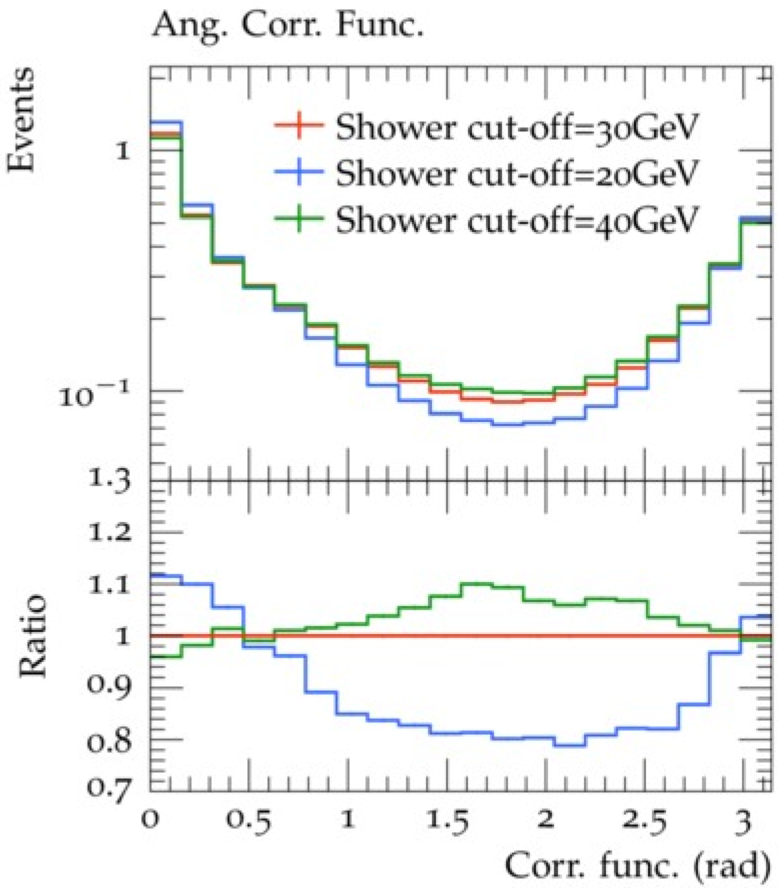
- Final predictions should be independent of shower cut-off
- However, hadronisation is not currently able to absorb these changes
  - For SM can re-tune hadronisation parameters, but not possible for dark showers
- Ongoing work on physically motivated cluster evolution should be able to alleviate this (see next talk by Stefan Kiebacher)



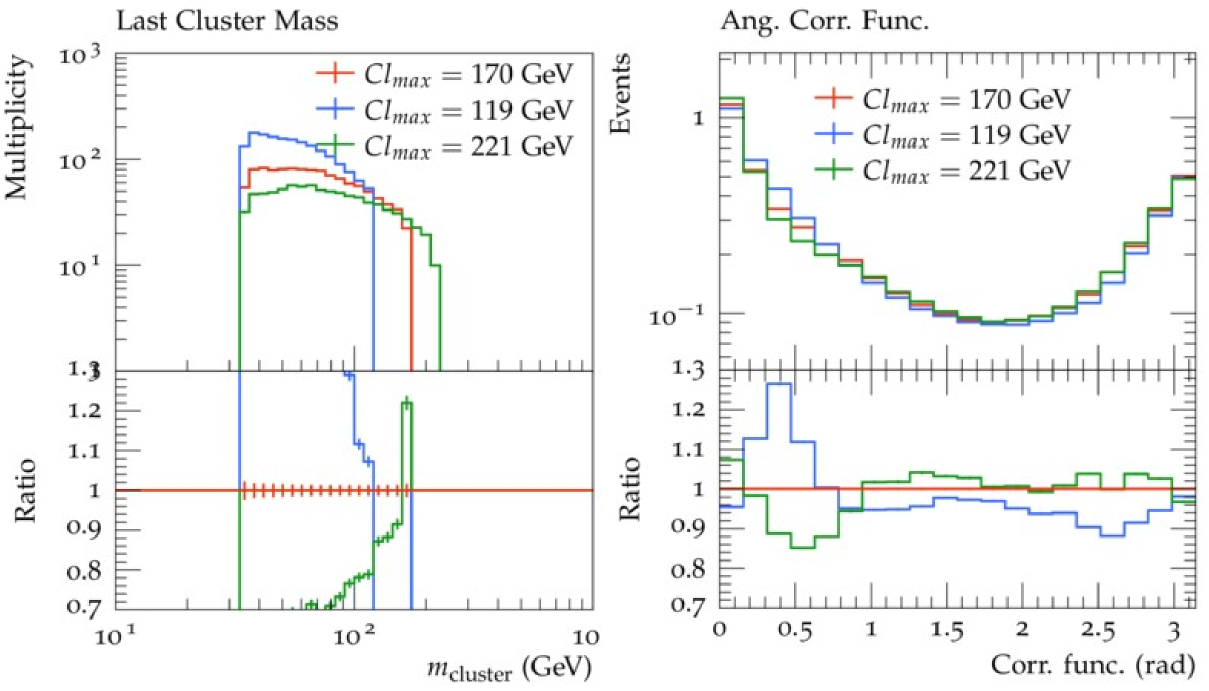
# Shower Cut-Off Variations

- Varied shower cut-off 10 GeV, keeping hadronisation parameters constant
- Lower shower cut-offs give more splittings from parton shower, which are more colinear than cluster fissioning
- Also reduces visible decay fraction from 56% to 50%



# Hadronisation Parameters

- Varied hadronisation parameters by tuning uncertainties or differences between light and heavy quarks
- Most notable is $Cl_{max}$ – scale above which clusters are fissioned
- Can cause visible decay fraction to vary from 44% to 61%
- Affects boost of $\rho_D$, and hence angular distance between $\rho_D$ decay products



# Conclusions and Outlook

- Dark shower model implemented into the Herwig generator
  - Will be included in Herwig 7.4 release
- Correlation functions reveal interesting jet substructure
- Good description of dark showers requires a more fundamental description of hadronisation
  - Ongoing efforts in Herwig to realise this and provide uncertainties on hadronisation

# Backup

# Dark Hadronisation

- Can predict the fractions of unstable $\rho_D$ relative to stable $\pi_D$ (and $\eta_D$, which decays to $\pi_D$)
  - In Pythia these are input parameters
- Varying the cluster fission scale could give estimate of uncertainties
  - Working on prescription for uncertainty estimation

| | | Pythia parameters | Herwig prediction |
|---|---|---|---|
| Invisible | $\pi_D$ | 42% | 43% |
| | $\eta_D$ | Neglected | 0.9% |
| Visible | $\rho_D$ | 58% | 56% |