Dark Shower Developments in Herwig

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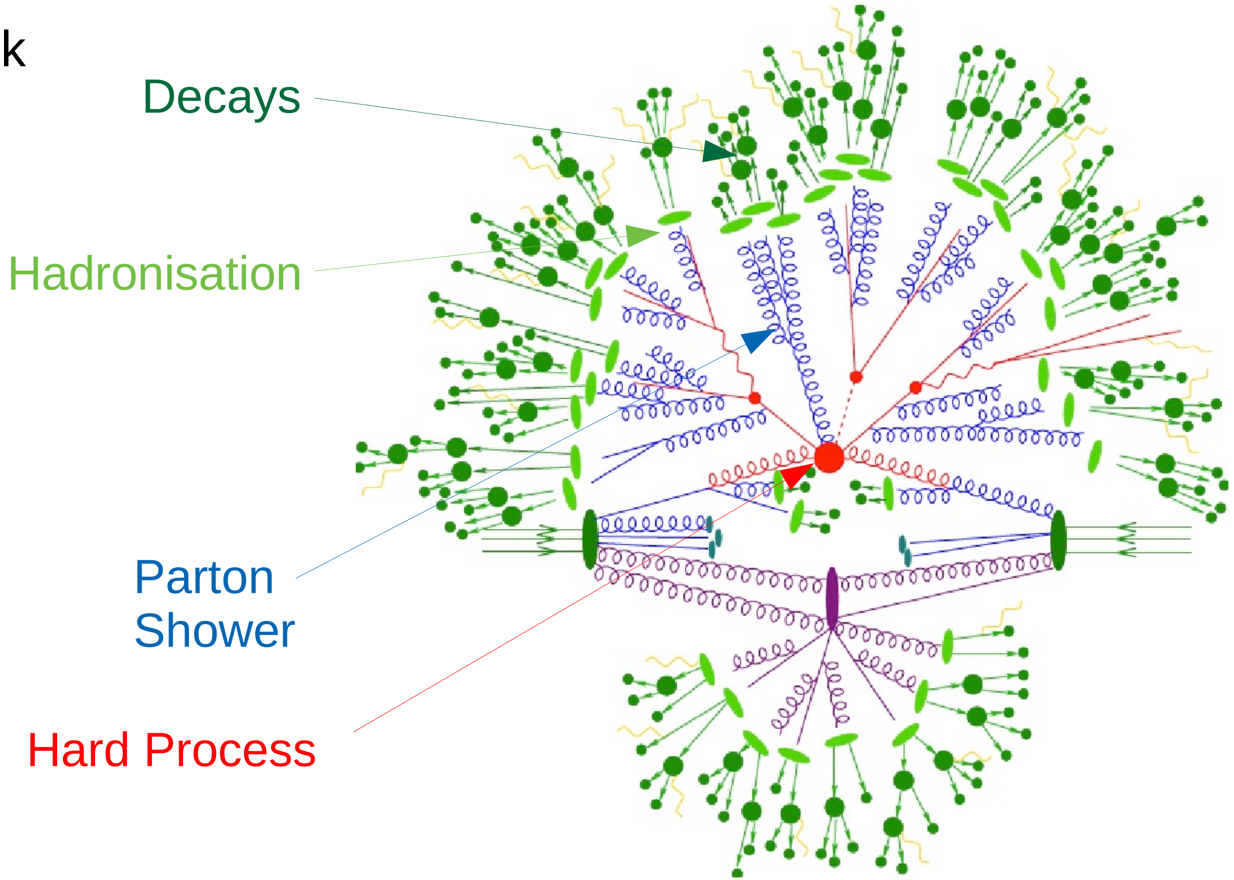
Motivation

- Unlike most BSM models, dark showers involve new physics at a range of energies
- Includes non-perturbative physics
  - described by semi-empirical models
  - Tuned to SM data
- Herwig uses different models to Pythia
  - Can act as cross-check
  - Is more predictive for some observables



Benchmark model

- For testing, took one of the proposed benchmark models from Snowmass 2021 report
- Dark quarks produced by 1 TeV dark photon, confined by an $SU(3)_{dark}$ symmetry
- Strength of dark force parameterised by the confinement scale Λ_D (α_D evolved using 2-loop running)
- Four mass-degenerate quark flavours
- Possible dark hadrons are pions (π_D), etas (η_D) and rhos (ρ_D)
  - Dark baryons not yet implemented, but plan to add these soon

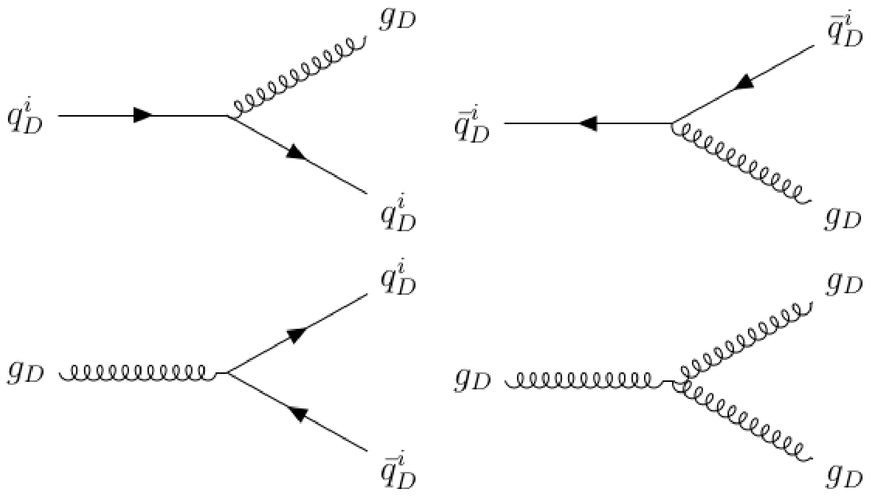
Benchmark model (cont.)

- $m_{\pi D}$ is a free parameter
- Other masses can then be estimated from lattice
- Take $m_{\pi D} = 1.7\ \Lambda_D$
  - $m_{\rho D} < 2\ m_{\pi D}$
  - π_D stable, ρ_D decay to SM particles
- Take benchmarks with $\Lambda_D = 10$ GeV and $\Lambda_D = 1$ GeV

Λ_D	1 GeV	10 GeV
$m_{\pi D}$	1.7 GeV	17 GeV
$m_{\rho D}$	3.18 GeV	31.8 GeV
$m_{\eta D}$	3.86 GeV	38.6 GeV
m_{qD}	0.955 GeV	9.55 GeV

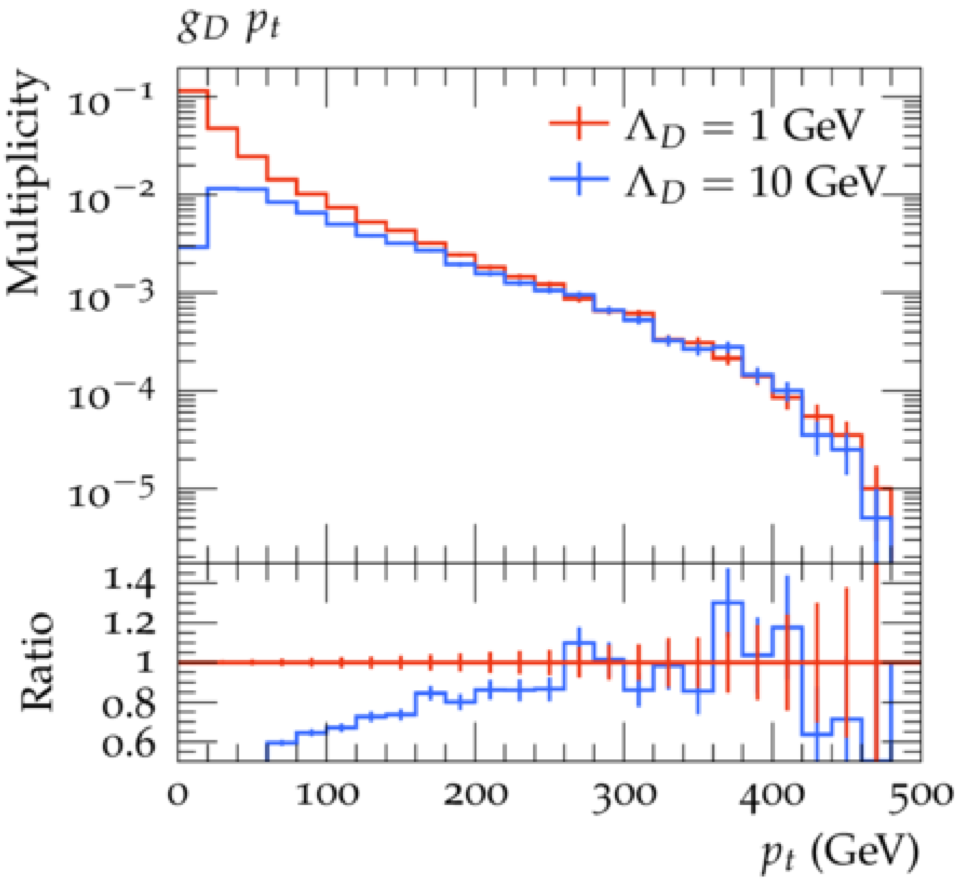
Dark parton shower

- The parton shower consists of a set of splitting kernels (**perturbative**)
- Based on BSM extension of Herwig angular ordered parton shower [Massoumina, in progress]
- Dark splittings now implemented, and can be turned on and off in configuration



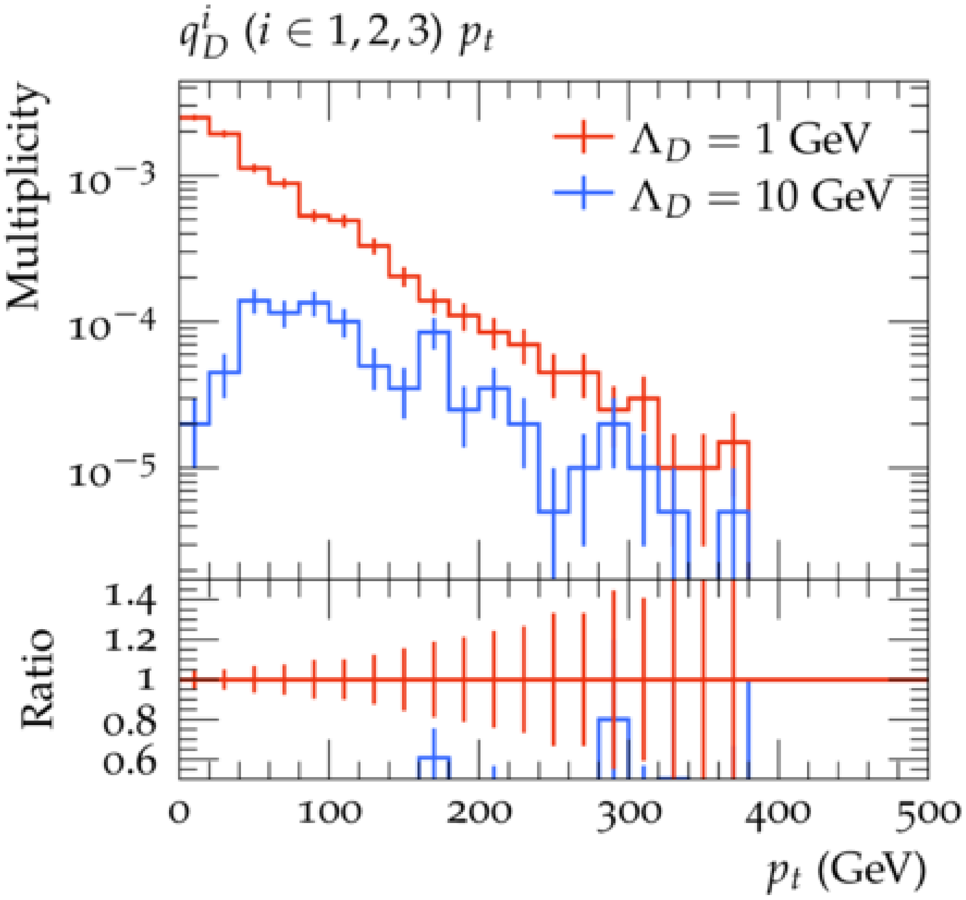
Dark parton shower validation

- For testing, generated events with dark photon decaying to only one flavour of dark quark (q_D^0), then emissions added by PS
- Shower adds a large number of gluons, especially at lower energies
- Low energy gluons suppressed for Λ_D = 10 GeV by shower cut-off



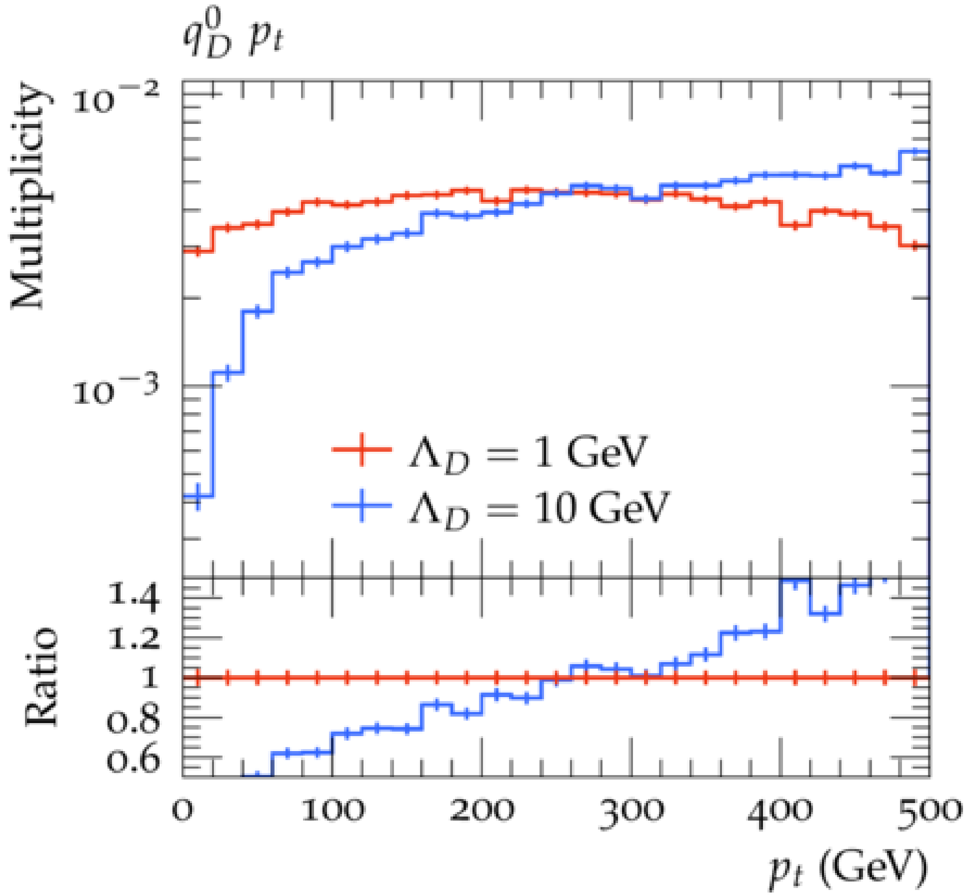
Dark parton shower validation

- Quark flavours 1-3 generated only by PS
- Quarks are produced much more rarely in the PS than gluons as these can only be produced by gluon splittings
- Especially true for Λ_D = 10 GeV due to high shower cut-off



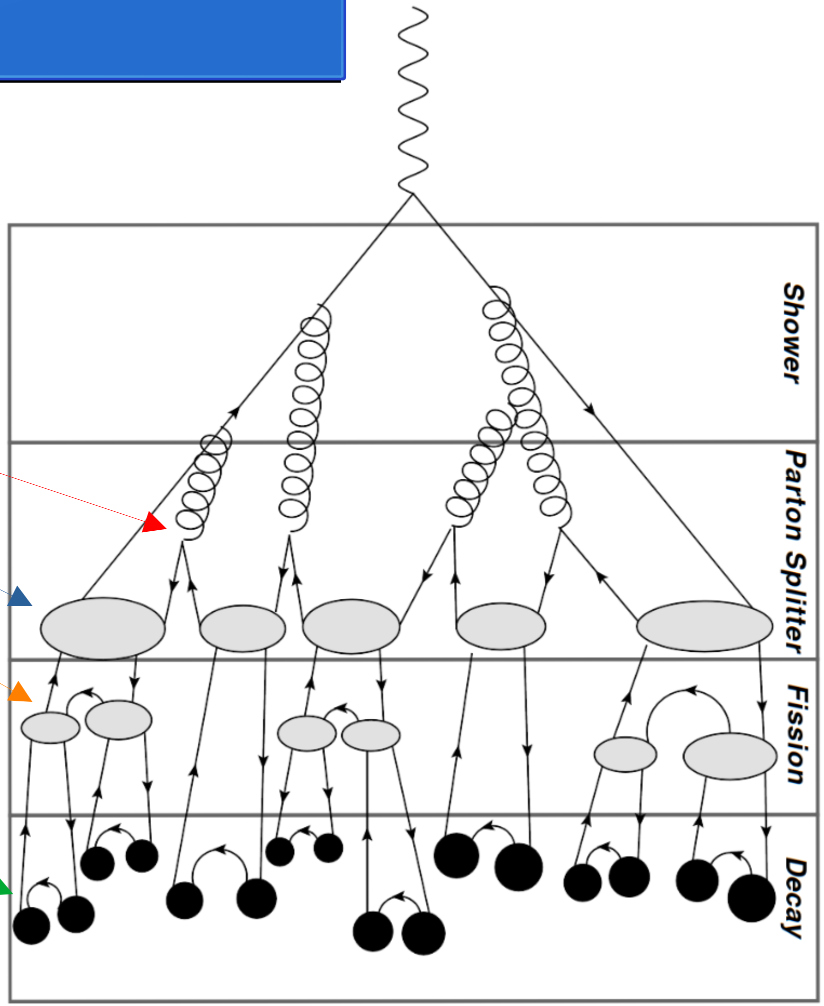
Dark parton shower validation

- Harder q_D^0 p_T spectrum for Λ_D = 10 GeV since fewer particles emitted
- Non-negligible fraction of events have q_D^0 p_T = 500 GeV (especially for Λ_D = 10 GeV) => high non-emision priority



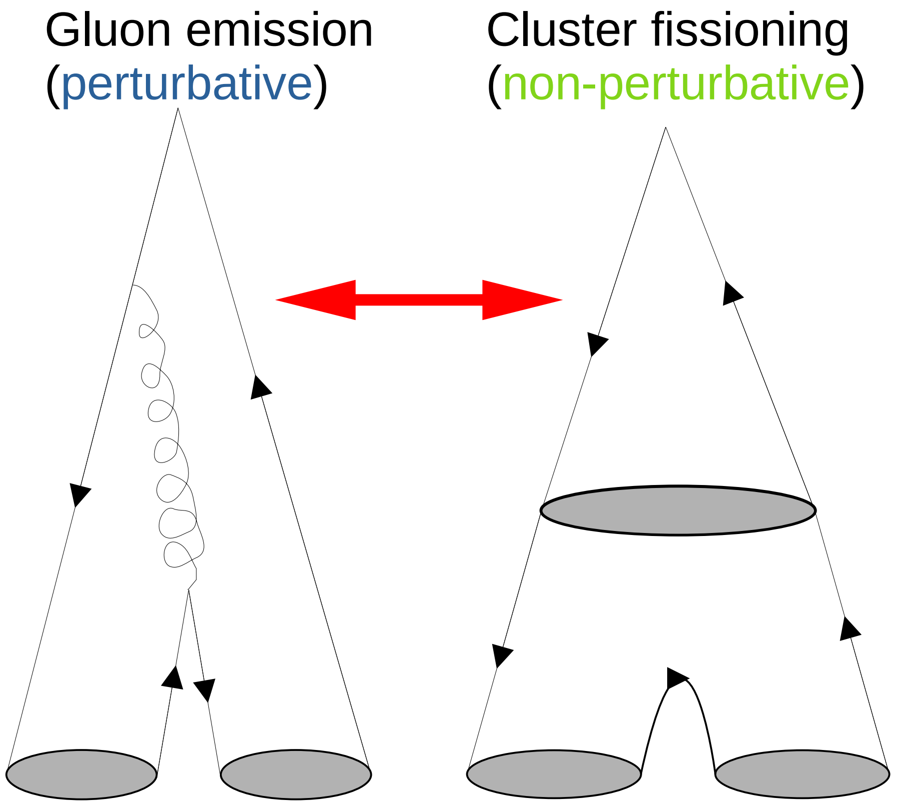
Cluster Hadronisation Model

- Hadronisation is **non-peturbative** => Semi-empirical models, tuned to SM data
- Herwig uses the cluster hadronisation model:
  - Gluons are split into qq pairs
  - Colour connected qq pairs form clusters (representing heavy pseudo-hadrons)
  - Very heavy clusters decay by springing qq pair from vacuum
  - Clusters decay to two hadrons (again by springing qq pair from vacuum) according to phase space and number of available spin-states



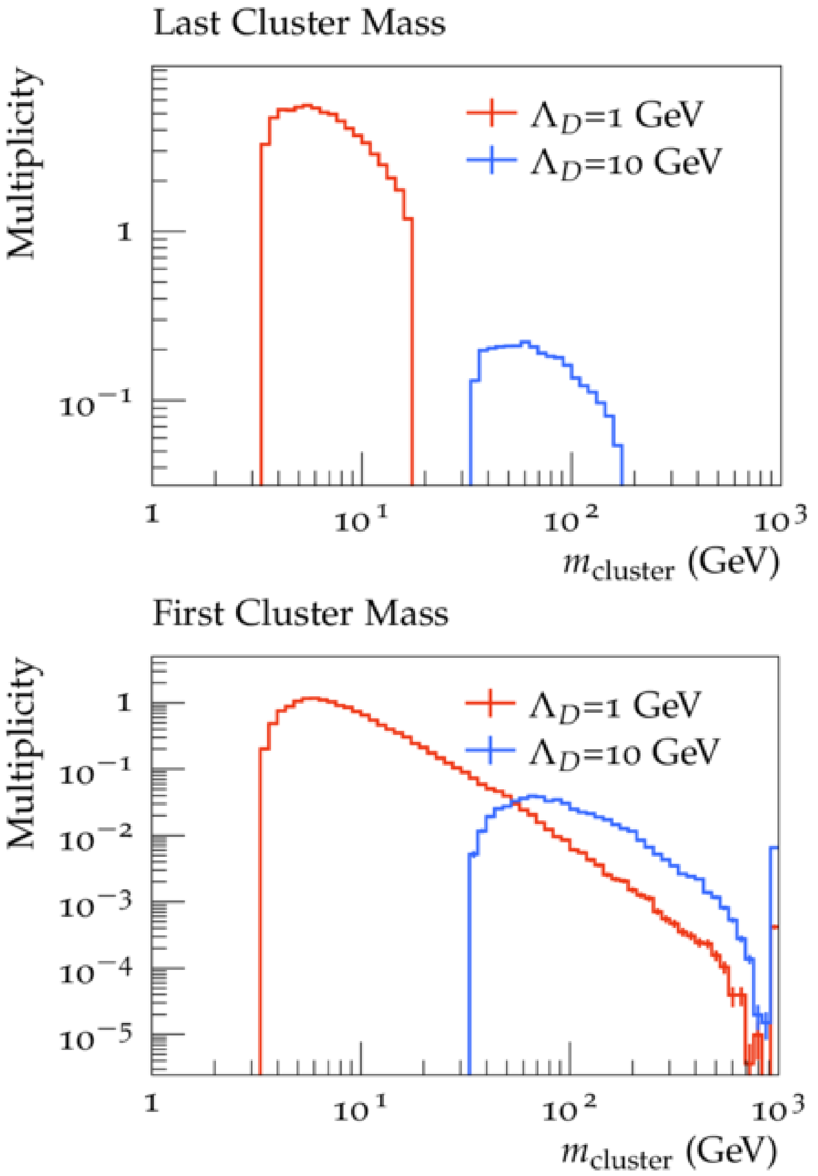
Dark Hadronisation

- Hadronisation code generalised to allow multiple confining interactions
- New DarkHadronSpectrum allows adding arbitrary spectrum of dark quarks and hadrons
- Free parameters must be assigned based on SM values and physical intuition
  - Ongoing work to give better physical motivations to these parameters



Cluster fissioning

- Initial clusters have large range of masses (down to minimum determined by shower cut-off)
- Very heavy clusters are unphysical (especially 1 TeV clusters due to no emissions in shower)
- Split clusters over 17 Λ_D (motivated by SM value)
- Parameters controlling mass of daughter clusters left at SM values



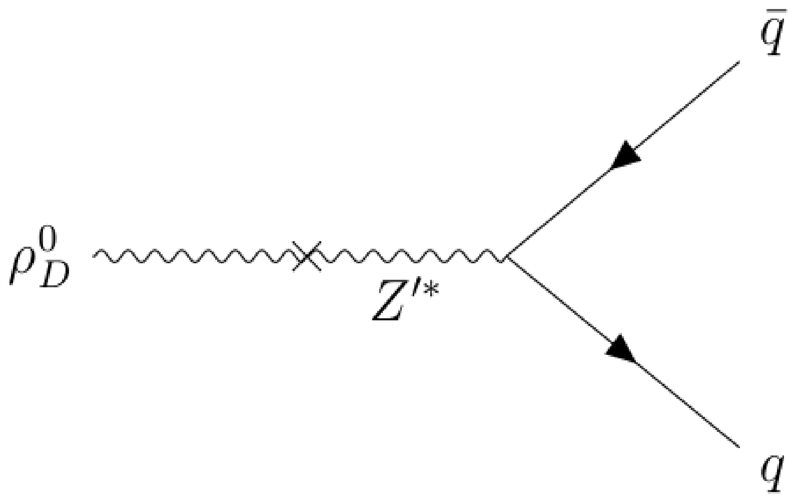
Hadron flavours

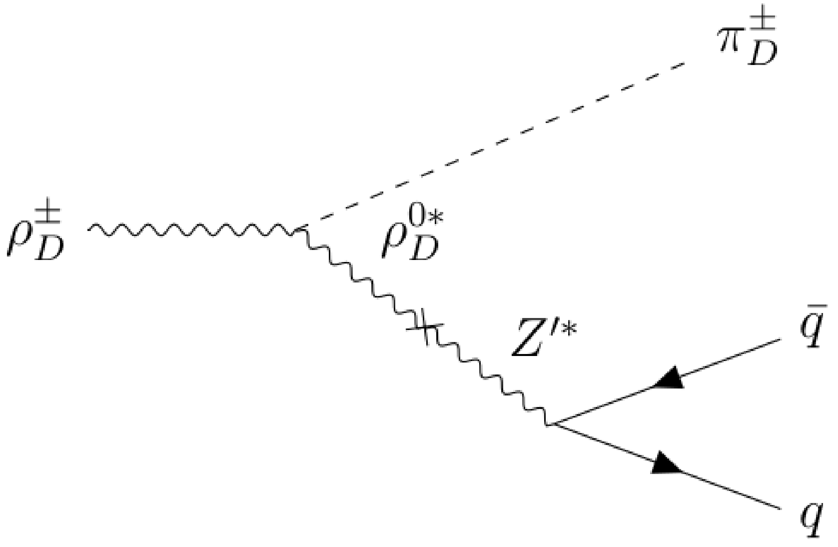
- The production rate of spin-1 to spin-0 mesons is a free parameter in Pythia's Lund string model
- Cluster hadronisation is predictive (based on phase space and spin states)
- Fractions of spin states obtained from Herwig provide useful check of recommended input values for Pythia

	Snowmass Pythia validation	Herwig prediction
π_D	42%	43%
ρ_D	58%	56%
η_D	Neglected for this benchmark	0.9%

Dark decays

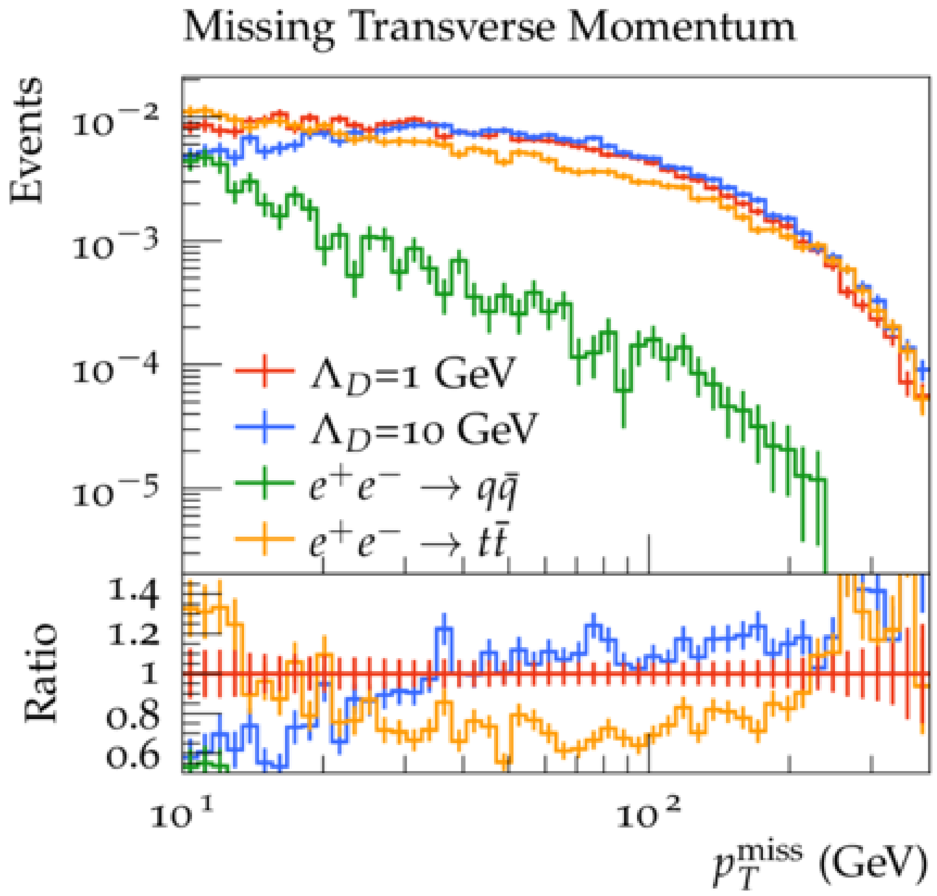
- Most decays can be implemented in input cards using existing Herwig classes
- For $\Lambda_D >> \Lambda_{QCD}$ dark hadrons will decay to free SM quarks
  - Can use existing quarkonium decayer
- New class added for three body decay to dark hadron + SM quarks
  - Parameters to control decay phase space still to be added





Phenomenological studies

- Currently working on sensitivity studies
  - Initially focusing on e^+e^- due to clean state
- Planning to study jet substructure variables such as angularities
- Will also serve as final validation of code



Outlook

- Dark shower model implemented in Herwig
- Phenomenological studies ongoing
- Aim to include in Herwig 7.4 release (early 2024), together with other hadronisation improvements (should reduce depency on SM tunes)
- Will provide useful complement to existing Pythia predictions