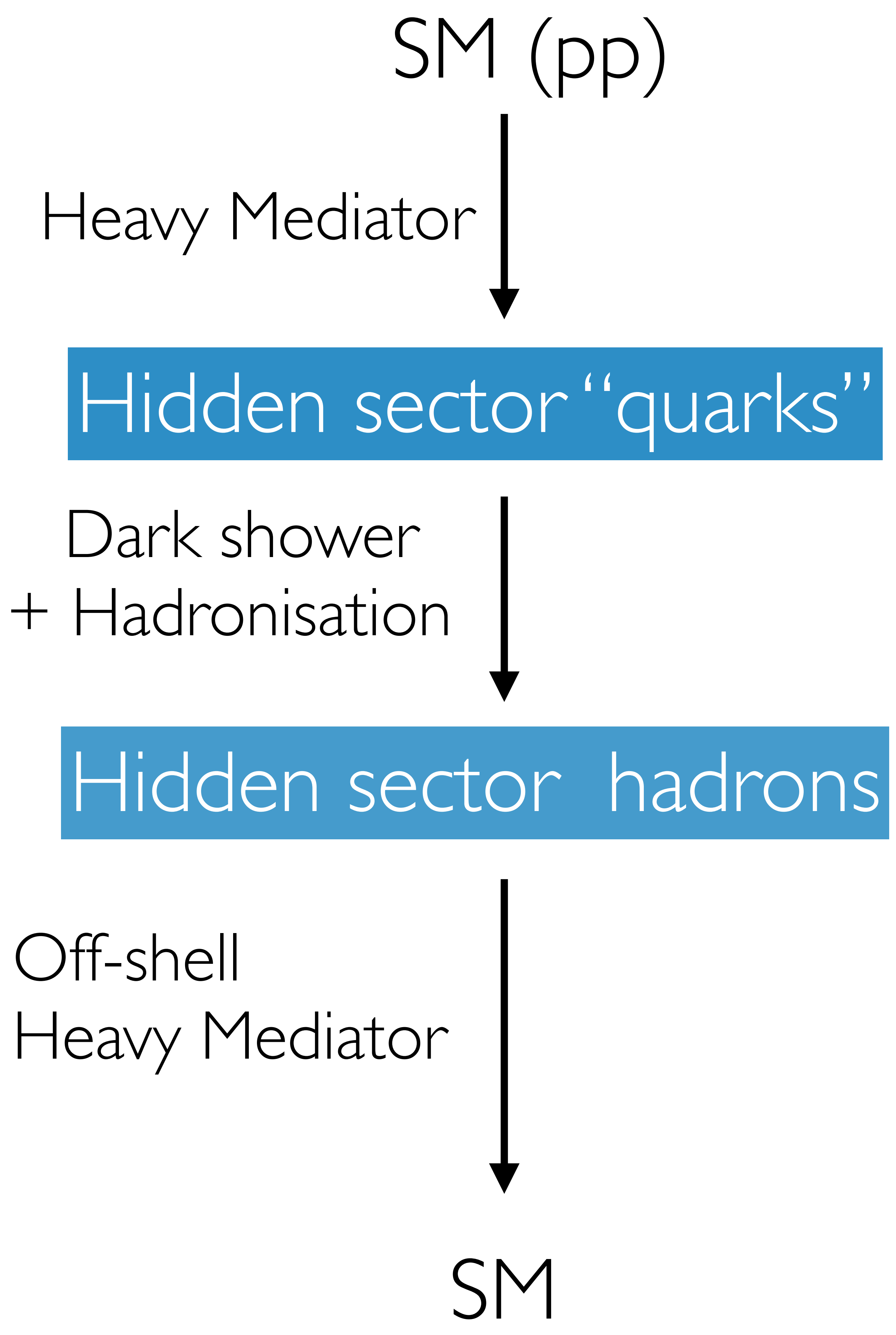
A simplified model for semi-visible or emerging jets

Nishita Desai, TIFR

Hidden Valley & Dark Showers

Hidden Valley: Strassler & Zurek hep-ph/0604261
Emerging jets: 1502.05409
Semi-visible jets: 1503.00009



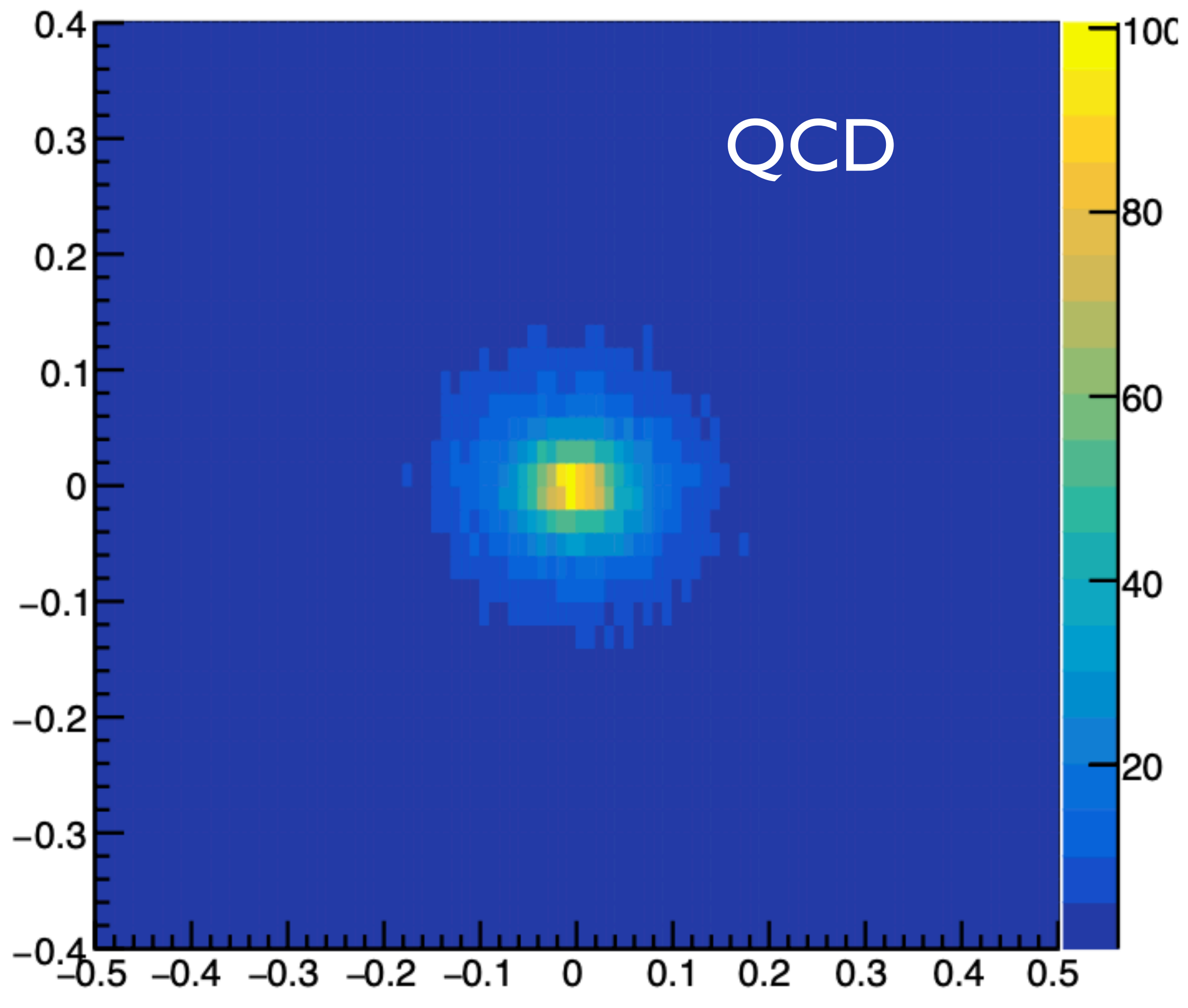
Dark Showers result in semi-visible jets

- Once you produce **dark quarks,** they will **emit radiation** like QCD-quarks
- The **dark quarks/gluons hadronize** to form dark mesons and baryons. The baryons and off-diagonal mesons would be stable but diagonal mesons can decay back to SM fermions via the same mediator
- When **dark mesons decay to charged SM mesons** or leptons, you can get displaced vertices
- A large fraction of the energy carried by the dark quark is un-observable, only a fraction **emerges back to the visible sector**
- **Missing energy is aligned with the direction of the jets** which also looks like mis-measurement.
- Pythia8 can do dark radiation (with coupling running) and hadronization (but user needs to specify colours, what is expected about flavours and decays)

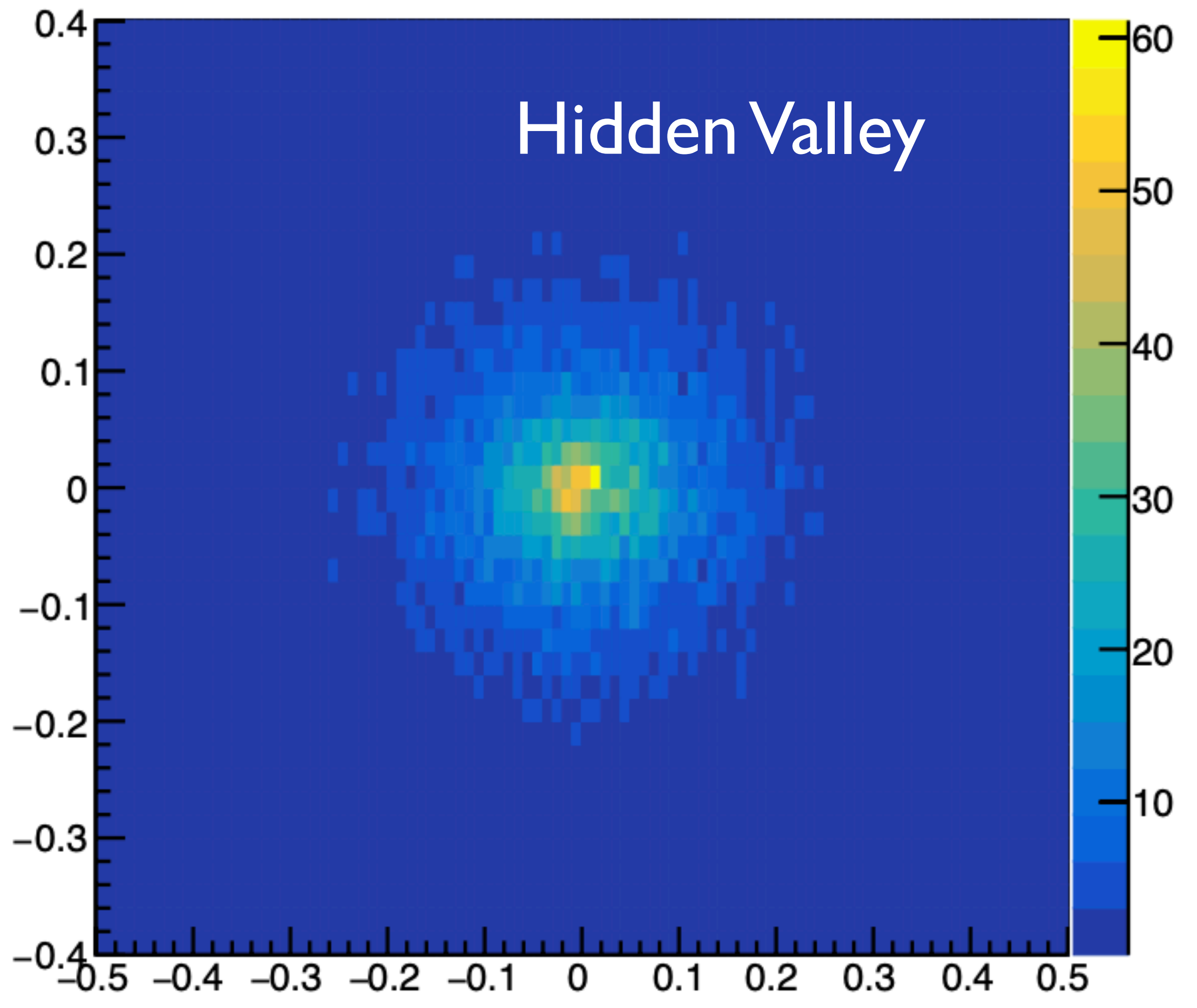
Dark showers look like pileup (noise from neighbouring collisions) or mis-measurement

What would be the best way to describe these?

- Current use of full Pythia8 machinery results in too many parameters (at a minimum, a scan in 8 dim; partly "tuning")
  - Number of flavours, number of colours, Hidden Valley scale (this sets beta function & coupling) [3] or fixed coupling [1+1]
  - Masses of mesons [2], masses of quarks [1]
  - Probability ratio of forming rhos to pions [1]
    Ratio of off-diag to diag set by combinatorics + [6] more hadronisation params (tuned to SM)
  - Decay tables of the individual mesons, especially any vectors [?]
  - Mass of mediator [1] + couplings to dark quarks [1] + coupling to SM quarks [1]

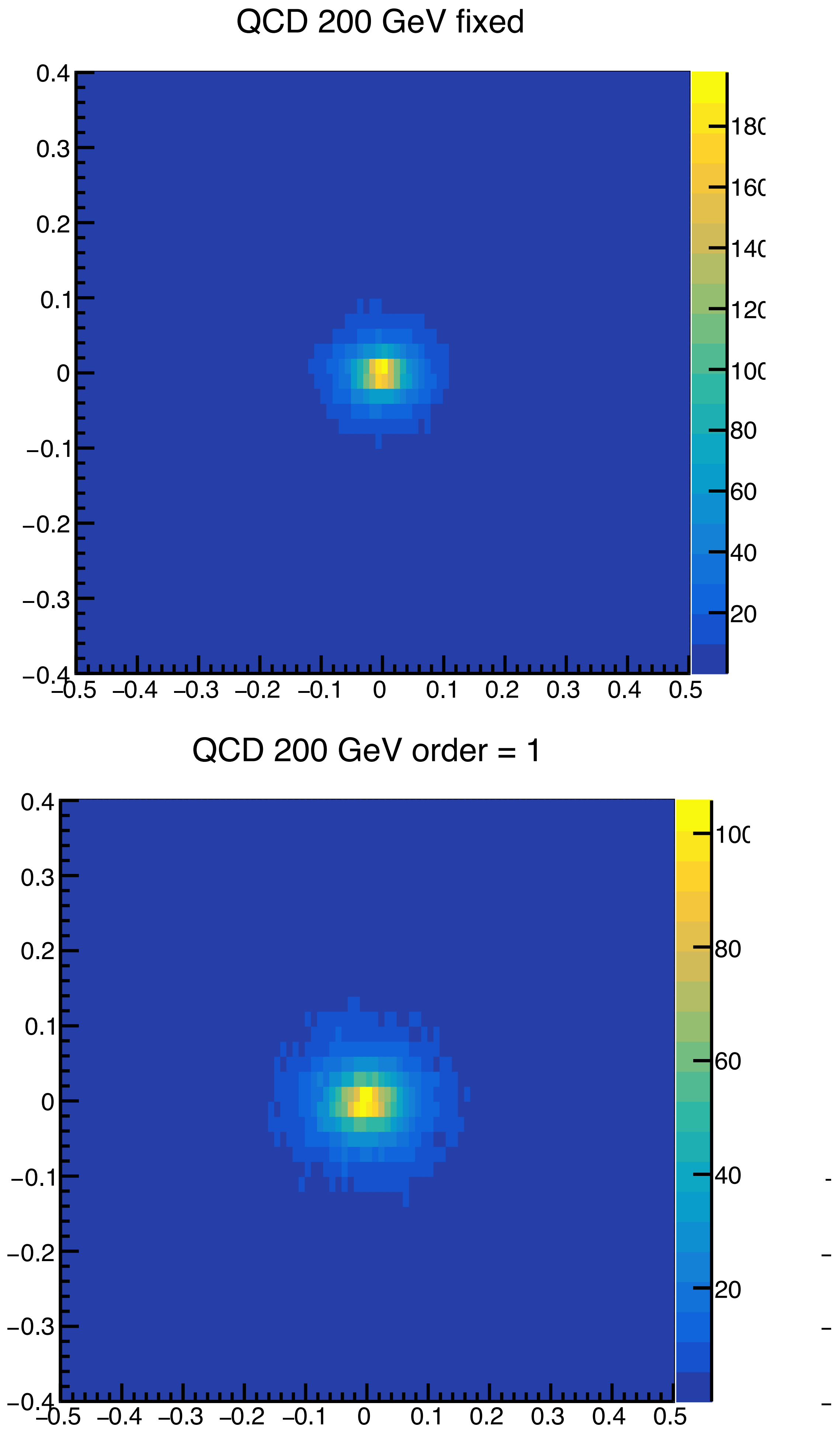


g=0.05, PV = 0.5, fixed

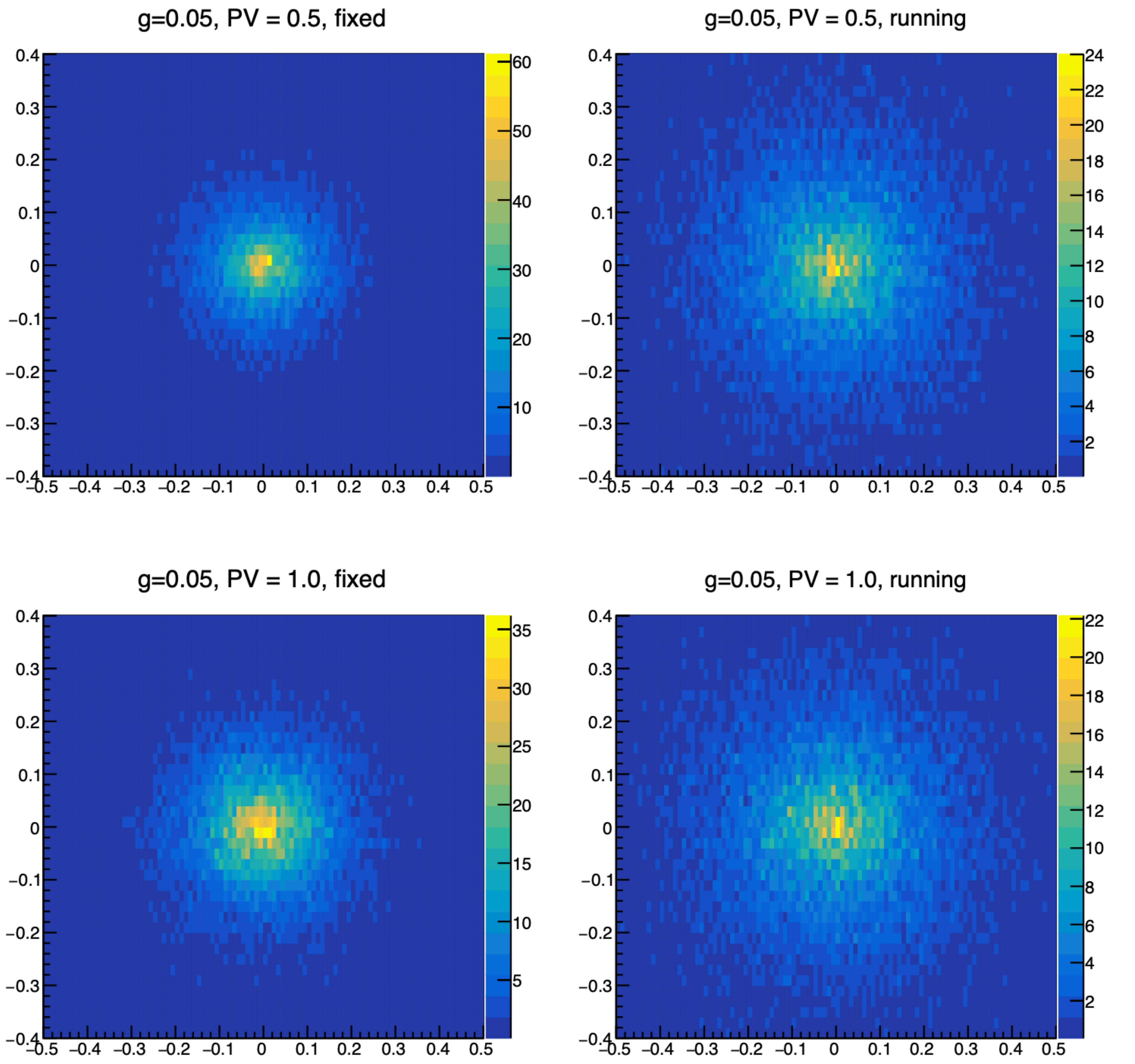


What are the parameters for simulation?

What are (if any) observable differences in energy distributions?



Lesson 1: running coupling results in wider jets

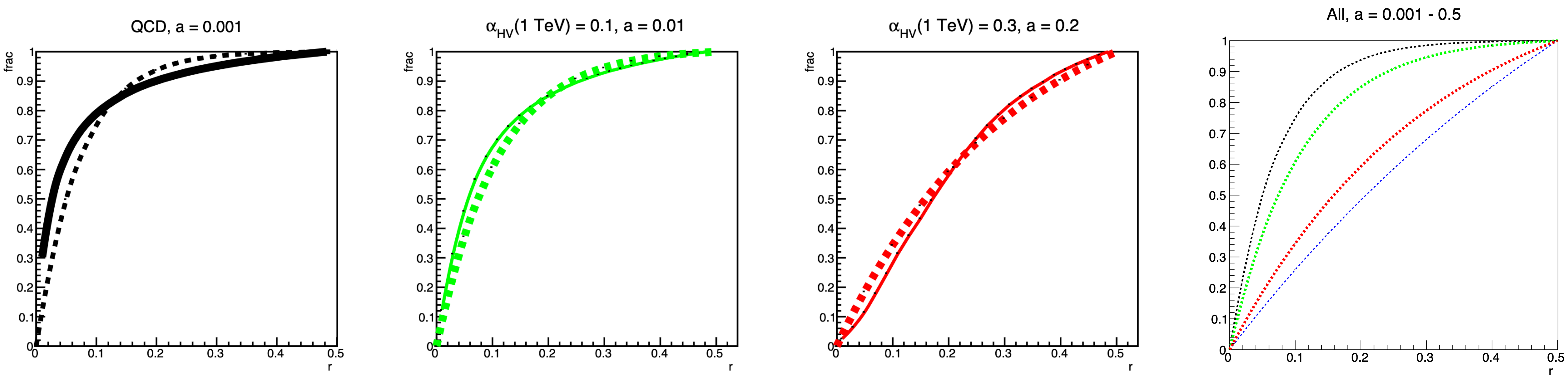


Lesson 2: Changing ratio of rho to pion production does not make a big difference in the end

A bottom-up model for semi-visible jets

- We only care about the visible fraction (1- rinv). Assume one kind of visibly decaying meson
- How does the energy of the dark quark translate into dark hadron jets?

$$f(r) = \frac{1 - a^{2r}}{1 - a^{2r_{\max}}}$$



- Use decay properties (lifetime, decay mode) of pions to make visible signal

Designing a simplified model

- Clearly, many choices result in similar phenomenology
- Can we encapsulate the difference meaningfully? —
  - **Mass of resonance** to set production kinematics [1]; UL on (sigma x B)
  - **Invisible ratio** to encapsulate fraction of invisible to visibly decaying hadrons [1]
  - Encapsulate the **jet shape** using our understanding of energy distributions
    - Needs number of mesons, choice of 'a' [2]
  - Simplified model-like **one kind of visible dark hadron decay at a time** [1] (mass)
- This also allows looking into specific channels (decays into b/c/tau, 4l, adding lifetime)

A realistic implementation

1. Jet radius parameter ($R_{\rm max}$).
2. Jet energy shape parameter $a = [10^{-3} - 0.5]$. As we shall see, this encapsulates the energy distribution as we go away from the jet axis.
3. Average number of dark hadrons (N_H)[1]
4. Fraction of invisible hadrons ($r_{\rm inv}$)
5. Mass of visibly decaying hadron ($M_{\rm H}$).
6. Decay table of visibly decaying hadron

Parameter	Range	Suggested values
$R_{\rm max}$	$[0.4, 1.0]$	0.5
a	$0.001 - 0.5$	0.001, 0.1, 0.3
$M_{\rm H}$	$1 - 100$ GeV	5, 9, 20 GeV
N_H	$1 - M_{Z'}/(2M_{\rm H})$	2, 10
$r_{\rm inv}$	$0 - 1.0$	0.2, 0.5, 0.8
Decay mode $\pi_{\rm H}$	$\ell^+\ell^-$, $q\bar{q}$ (particular cases $c\bar{c}, b\bar{b}$), $\gamma\gamma$	

Also see
arXiv:2103.0123 (Knapen, Shelton, Xu)

Current status: **Z' production works**, currently working to get it to correctly identify dark sector when using Madgraph with multi-jet merging

Another thing to consider: Production modes and challenges

Other realistic models for producing dark sector

What is the mediator? — Scalar (Higgs portal), Vector (Kinetic mixing of Z')

- A scalar that does not couple directly to SM fermions but only to SM Higgs via portal couplings

$$\mathcal{L} = m_{q_D}(\bar{q}_D q_D)S + \mu_1 S|H_{\rm SM}|^2 + \mu_2 S^2 |H_{\rm SM}|^2$$

Mixing of new scalar with SM Higgs, produced ~ $(\text{mixing}/M_S)^2$

OR Produce SM Higgs and look at non-SM decay ~ $(\text{mixing})^2$

- New U(1) with couplings to dark quarks. Coupling to SM quarks comes from kinetic mixing with the photon

$$\mathcal{L} = \varepsilon F^{\mu\nu} Z'_{\mu\nu} + g_D(\bar{q}_D \gamma^\mu q_D) Z'_\mu$$

Produce Z' via the small mixing. Also visible in dijet/dilepton searches ~ $(\text{mixing})^2$

Triggers for Dark Showers

Mono-jet is not ideal because background is pure QCD multijet

There is a limit to how fast the detector can react. Thresholds (triggers) ensure rejection of QCD events.

Since our event looks "weird", we need to rely on some extra SM-like part that can be triggered on. Usually, this is a "mono-jet" (i.e. one jet coming from initial state radiation since quarks and gluons from proton can always give some)

Trigger	**Typical offline selection**	**Trigger Selection**		**L1 Peak Rate [kHz]**	**HLT Peak Rate [Hz]**
		L1 [GeV]	HLT [GeV]	$L=2.0\times10^{34}$ $cm^{-2}s^{-1}$	
Single jet	Jet ($R = 0.4$), $p_T > 435$ GeV	100	420	3.7	35
	Jet ($R = 1.0$), $p_T > 480$ GeV	111 (topo: $R = 1.0$)	460	2.6	42
	Jet ($R = 1.0$), $p_T > 450$ GeV, $m_{jet} > 45$ GeV	111 (topo: $R = 1.0$)	420, $m_{jet} > 35$	2.6	36

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A quick calculation using MC (MadGraph5, 1106.0522):
Z + 1 jet (jet > 20 GeV) 2323 pb; using mono jet criterion 0.297 pb

Triggers for Dark Showers

For scalar-mediator, use VBF or top-associated production

- **Vector boson fusion topology** has two well-separated jets: VBF trigger has smaller requirement on jet p_T + invariant mass requirement e.g. (p_{T1} >150, p_{T2} >40, m_{jj} >650) GeV

- Top decays either into 3 jets or jet + lepton + MET. Very easy to satisfy one trigger for ttbar. E.g. single/double lepton, or multijet (jets > 4). Also possible with single top + jet but cross section is not great.