Dark Showers @ LHC

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What is the idea?

There is a hidden, confining sector similar to SM QCD.

Any new fermions of this sector are singlets under SM gauge groups

We can access this dark sector via a “portal” — this can be vector or scalar

If we produce dark fermions through this portal at LHC energies, you would expect QCD like “parton” showers and hadronization to eventually form dark hadrons

These dark hadrons are invisible, but because of the portal some of them might decay back to SM mesons/leptons. This results in unusual signatures.

Three frontiers

Model building — determine the requirements from e.g. dark matter, baryon asymmetry etc.

Signature building — what should it look like in the detector? What are best triggers (often based on accompanying SM)?

Monte Carlo — can we encapsulate reasonable phenomenological possibilities in our simulation that can be used by experiments?

Some community work

LLP community document: 1903.04497

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Snowmass: 2203.09503

Theory, phenomenology, and experimental avenues for dark showers: a Snowmass 2021 report

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Theory motivations

Early ideas from 1990-92 mainly motivated by baryon and dark matter densities

Based on a U(1) mediator (or Higgs that breaks the new U(1))

Kaplan (1992), Barr et al (1990, 1991), Dodelson et al (1992), Kuzmin (1997)

Based on t-channel scalar

Kitaev & Low (2004)

Based on Higgs decays

Strassler & Zurek (2006), Kaplan et al (2009)

Hidden Valley

Strassler & Zurek (hep-ph/0604261)
Han et al (0712.2041)

First idea of looking at hidden sectors at hadron colliders.

Adding a $U(1)_X$ x $SU(N_D)$ to the SM along with 2 dark quarks* and 3 RH neutrinos

$U(1)_X$ charges determined by anomaly cancellation conditions

All dark sector hadrons except the neutral pion are stable. Lifetime of the dark pions calculated based on certain minimal assumptions; mainly decay via Z' to SM fermions. Decay is helicity suppressed therefore massive fermions favoured.

* Originally valley quarks, but renamed here to make notation uniform

Pythia8 implementation

Carloni & Sjöstrand (1006.2911, 1102.3795)

Updated v8.306 for Snowmass

Dark Final State Radiation

`Ngauge, Nflav, Lambda`

$$\alpha_D(\mu^2)N_D = \left[\frac{1}{2\pi}\left(\frac{11}{3} - \frac{2}{3}\frac{N_f}{N_D}\right)\log\left(\frac{\mu}{\Lambda_v}\right)\right]^{-1}$$

Dark Hadronisation: multiple parameters

`HiddenValley:aLund, HiddenValley:bmqv2, HiddenValley:rFactqv, HiddenValley:sigmamqv`

+ Masses of dark quarks and individual mesons (separate meson flavours can be given different masses.

General phenomenological ideas

Lifetime of decaying dark sector particles will determine how it shows up in the detector

Promptly decaying to SM; prompt jets but look different than QCD jets? E.g. more photons, more leptons (e.g. 1002.2952), different substructure (e.g. 2004.00631) etc.

Intermediate lifetimes mean some decays in tracker. Gives displaced vertices, displaced leptons, displaced jets

Larger lifetimes result in decays in calorimeters. Results in trackless jets

Decay out of detector results in MET.

General phenomenological ideas

Three main components:
- Production mechanism
- Showering and hadronisation in the dark sector
- Decay of dark mesons into SM visible objects

If dark sector is fully invisible on detector scale, production cross section needs to be large enough to survive mono-X or MET searches

For unusual signatures, we do not know if they will be visible with standard **triggers**; best trigger depends on production mode: e.g. VBF or leptons from gauge boson in VH where H then decays to dark sector.

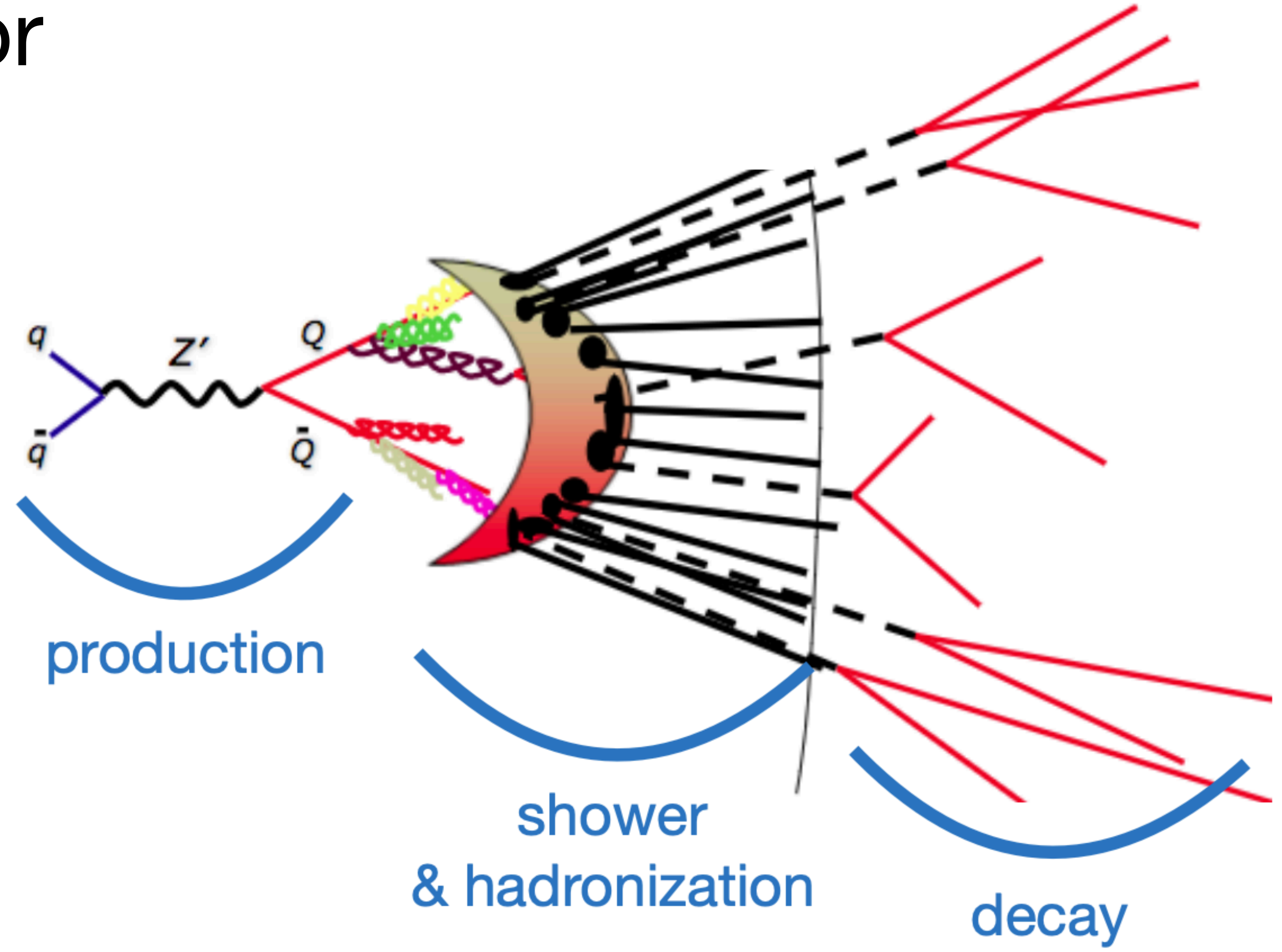


Figure from 1903.04497 & 0806.2385

*Expected phenomenology**

Emerging jets / trackless jets

Lepton jets

Displaced vertices or displaced leptons

Heavy meson decays

Heavy meson jets

Missing energy searches

Higgs invisible width or weird decays of Higgs

Top decays

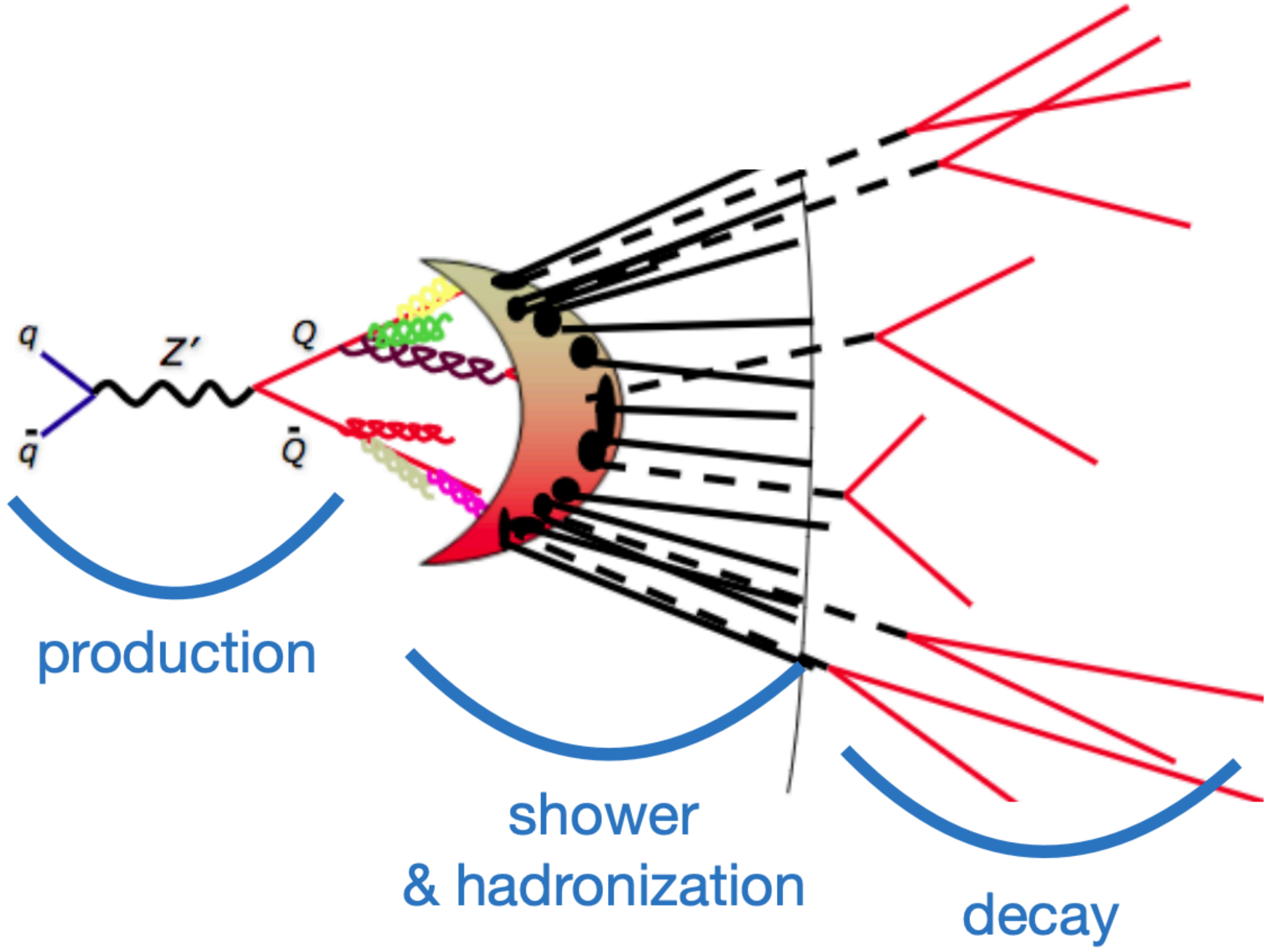


Figure from 1903.04497 & 0806.2385

***Direct searches for mediators are also important**

Idea: displaced vertices

Zurek & Strassler hep-ph/0605193

Since dark pions decay back into SM quarks with finite lifetime, this will result in SM charged mesons that make a displaced vertex.

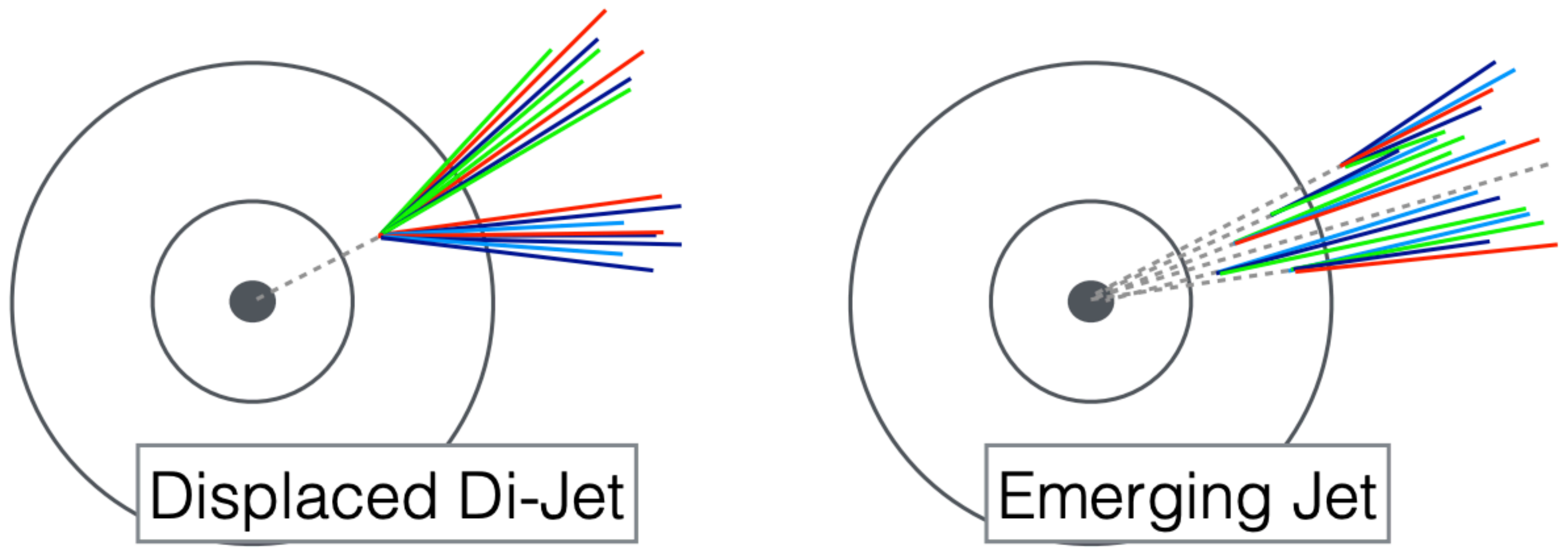
Multiple ATLAS & CMS experimental searches for displaced jets and DV using jets/muons/MET for triggers. (See talks by Darwish and Henry following)

For light mediators, displaced vertices at low(er)-energy e+e- experiments would yield better constraints.

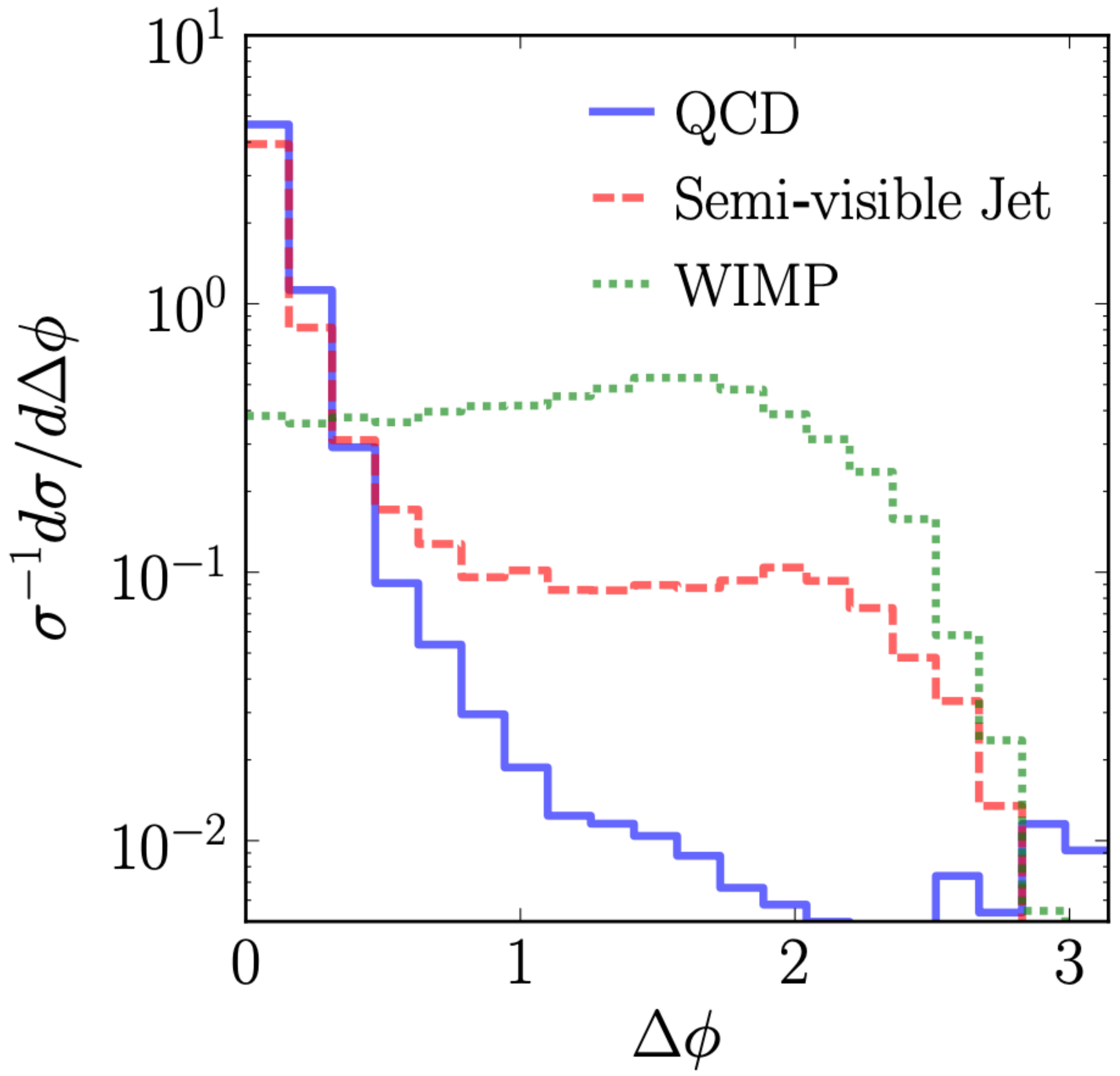
See e.g. Graham et al 2104.10280 for recent review of dark photon searches,
Bernreuther et al 2203.08824 for dark showers at Belle II

Idea: Emerging or semi-visible jets

Schwaller et al. 1502.05409



Cohen et al. 1503.00009

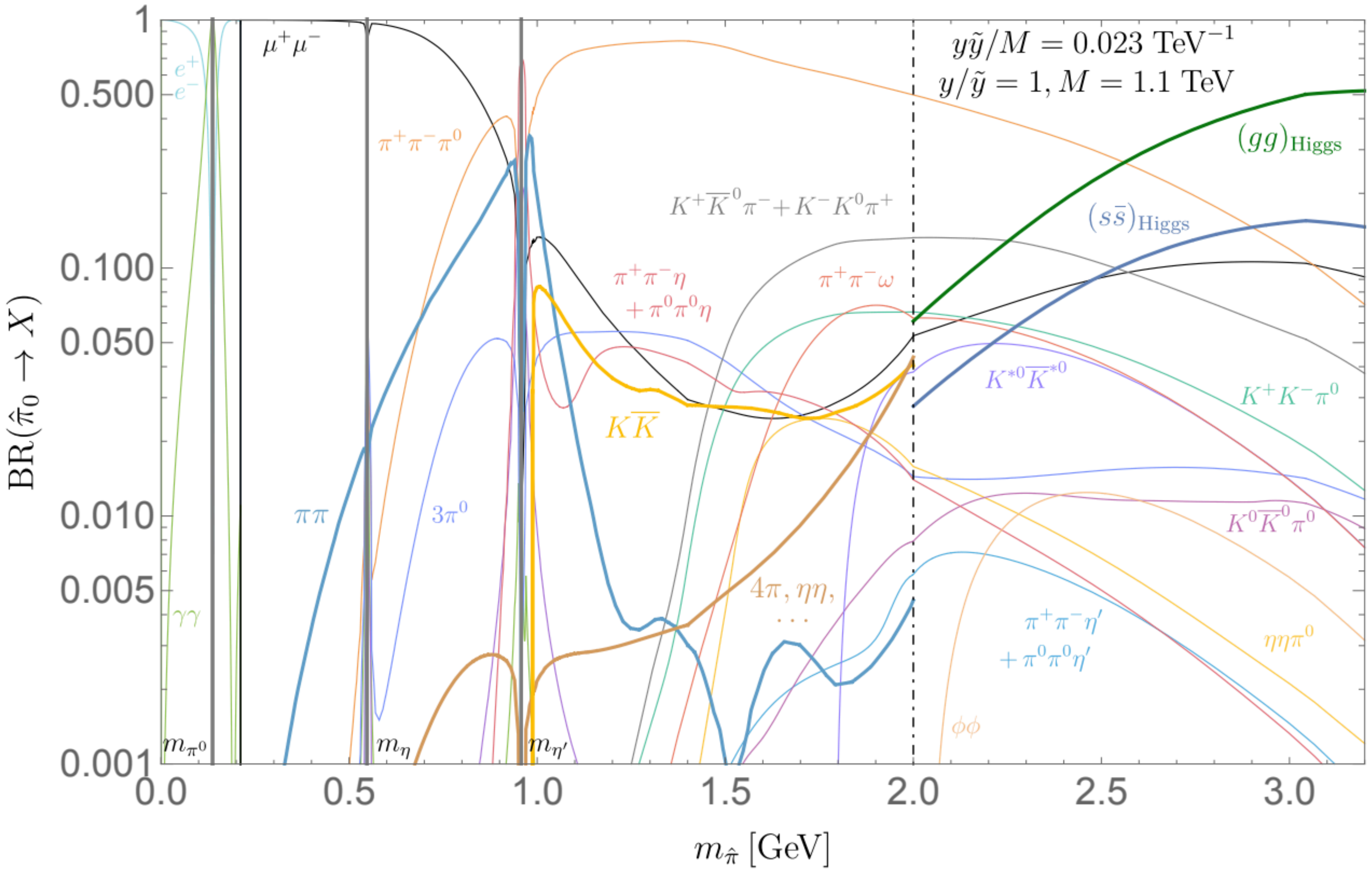


In general result in few (or no) tracks. There is missing energy, but aligned with one of the jet axes

Idea: Meson decays

Cheng et al (2110.10691)

Dark pions would directly decay into SM mesons. Calculation is complicated and model dependent. Based on Z-portal or Higgs-portal to dark quarks. Dark pions mix with Higgs if scalar, Z if vector and new ALP if pseudo-scalar.



Multi-meson final states could be identified at e.g. LHCb

They also identify FCNC decays of SM mesons B → K + inv and K → π + inv.

Current bottlenecks

Top-down or bottom up? — since we don't know anything bottom-up seems sensible BUT we need to start somewhere and natural bias goes to easier to detect or calculate first. Can we make modular **benchmarks**, i.e. benchmarks where production mechanism, showering and hadronisation mechanism, and decay of dark hadrons is separable?

Simulation tools are preliminary. There is no data to tune showering and hadronisation models. There has been no need so far to implement a more complex dark hadron sector.

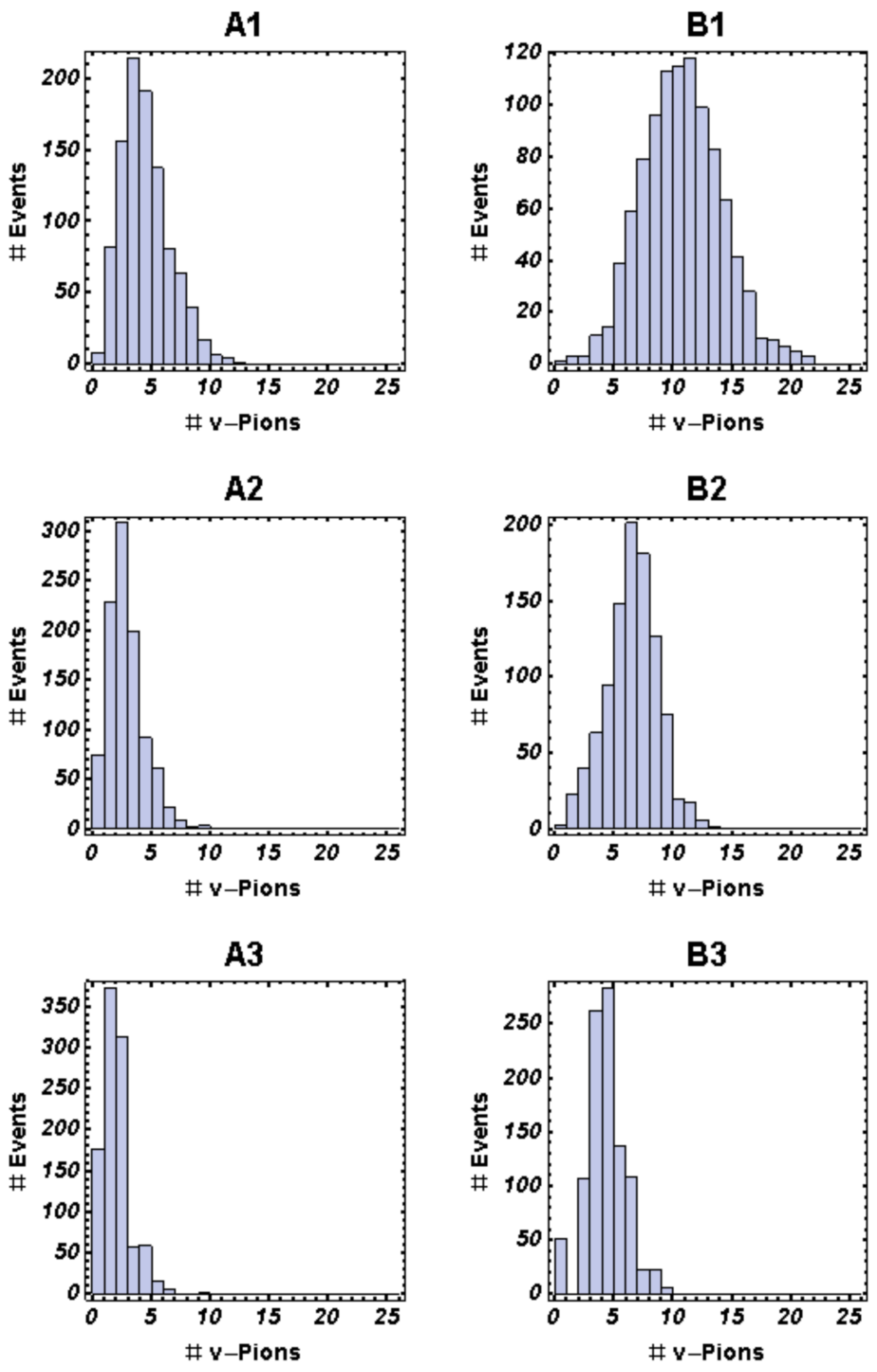
What are the correct/useful IRC safe variables? Preliminary studies based on counting how many dark hadrons decay into SM visible.

How to make benchmarks?

Case 1) Production through Z’. Based on Pythia HV, with 3 colours, 2 dark flavours. Triplet of pions that decays primarily to heavy flavour following original HV idea.

Λ_v/Λ_{QCD}

Case	$\pi_v^{\wedge}$ stable?	m_{π_v} (GeV)	R	$\#\ \pi_v$ decays	$\hat{H}_T$ (GeV)	M_4 (GeV)	$\not\!\!E_T$ (GeV)
A1	Yes	50	368	4.0	667	590	318
A2	Yes	120	883	2.4	765	667	400
A3	Yes	200	1470	1.5	886	770	459
B1	No	50	368	10.3	1650	1427	214
B2	No	120	883	6.1	1835	1562	182
B3	No	200	1470	3.9	2248	1810	145



Number Distribution of Visibly−Decaying v−Pions

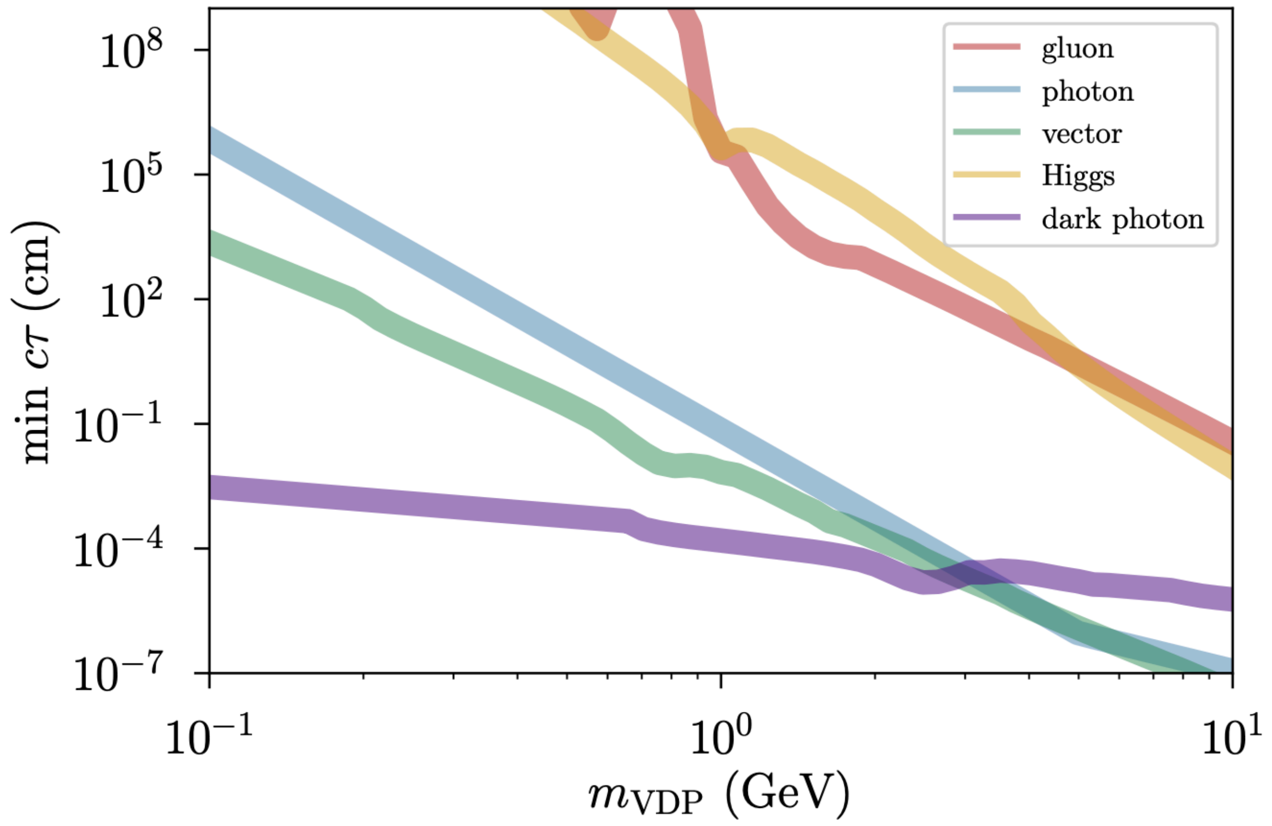
Strassler 0806.2385

How to make benchmarks?

Case 2) Production via Heavy Scalar that decays to dark quarks; Pythia HV for showering but decay of dark hadrons via EFT description

Introduces the idea of the Visibly Decaying Particle (i.e. the dark hadron that decays to SM). Spin-0 and spin-1 mesons in final state. Observability then depends on the nature of VDP decay; they propose five portals for decay.

Decay portal	decay operator	VDP	other dark hadron	features
A. gluon portal	$\tilde{\eta} G^{\mu\nu} \tilde{G}_{\mu\nu}$	$\tilde{\eta}$	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	hadron-rich shower
B. photon portal	$\tilde{\eta} F^{\mu\nu} \tilde{F}_{\mu\nu}$	$\tilde{\eta}$	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	photon shower
C. vector portal	$\tilde{\omega}^{\mu\nu} F_{\mu\nu}$	$\tilde{\omega}$	$\tilde{\eta}$ stable	semi-visible jet
D. Higgs portal	$\tilde{\eta} H^{\dagger} H$	$\tilde{\eta}$	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	heavy flavor-rich sh
E. dark photon portal	$\tilde{\eta} F'^{\mu\nu} \tilde{F}'_{\mu\nu} + \epsilon F'^{\mu\nu} F_{\mu\nu}$	A'	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	lepton-rich shower



Source: Knapen et al 2103.01238

How to make benchmarks?

Case 3) More complicated dark flavour sector. Showering/hadronisation with Pythia HV, decay to visible mainly because of mixing with Higgs that breaks U(1)

Regime	N_c, N_f	Λ_v [GeV]	**Q**	m_{π_v} [GeV]	m_{ρ_v} [GeV]	Stable dark hadrons	Dark hadron decays
$m_{\pi_v} > m_{\rho_v}/2$	3,4	10	(-1,2,3,-4)	17	31.77	All π_v	$\rho_v^0 \to q\bar{q}$ $\rho_v^\pm \to \pi_v^\pm q\bar{q}$
$m_{\pi_v} < m_{\rho_v}/2$	3,3	5	Various	3	12.55	$0/1/2\pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$
	3,3	10	Various	6	26	$0/1/2\ \pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$
	3,3	50	Various	30	125.5	$0/1/2\ \pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$

Snowmass 2203.09503

How to design IR safe variables?

A common variable dependent on number of hadrons (Cohen et al 1707.05326)

$$r_{\rm inv} \equiv \left\langle \frac{\#\text{ of stable hadrons}}{\#\text{ of hadrons}} \right\rangle$$

# of hadrons is not IR safe; is the ratio approximately IR safe?

Jet substructure: Cohen et al 2004.00631

$$e_2^{(\beta)} = \sum_{i<j\in J} z_i z_j \left(\theta_{ij}\right)^{\beta} ,$$

$$z_i \equiv p_{T_i}/p_{T_J} \text{ and } \theta_{ij} \equiv R_{ij}/R_0$$

Discriminating dark shower from ordinary QCD is similar to q/g in QCD; use angular spread of radiation

Use “error envelopes” to capture uncertainty due to showering and hadronisation.

LHC LLP WG interests

1. Make a repository of modular benchmarks that can be kept updated with the field

2. Study effects of showering and hadronisation and how to encapsulate that uncertainty given fact we have no data to tune MC in the dark sector; identify variables that do not depend on these

3. Keep a repository or instruction document for simulation techniques that can be followed by new analyses.