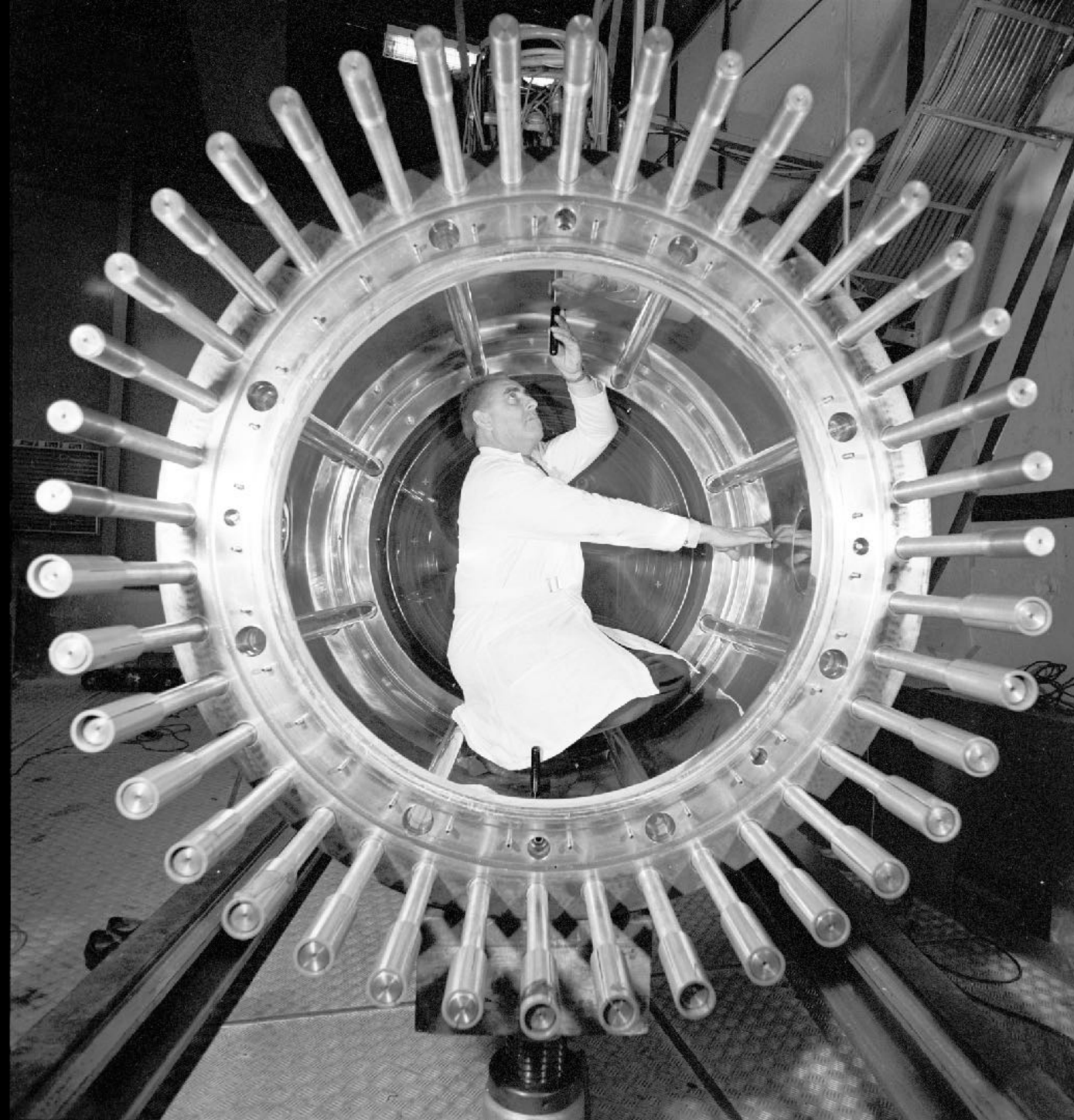
Dark showers and dark QCD

Experiences from the
LLP Community initiative

Past, present, future

James Beacham
Duke University

Dark Showers Benchmarks
Snowmass LoI Meeting
15 October 2020



Dark showers within The LLP Community initiative

The Long-Lived Particle Community (LHC experiments, theory/pheno, fixed-target experiments around the world, future experiments, etc.) initiative was formed at the LHC in 2016 as a collaborative platform to ensure we don't miss LLP signatures at the LHC and beyond — and dark showers have been one of the main topics of interest from day one

First LHC LLP Mini-workshop, 2016

Classification?

	Prompt	Displaced	Detector Stable	
Emerging Jet		X		
Semivisible Jet	X		X	
Semi-displaced Jet	X	X		New!
Escaping Jet		X	X	New!

P. Schwaller, Dark Showers WG talk, April 2017 workshop

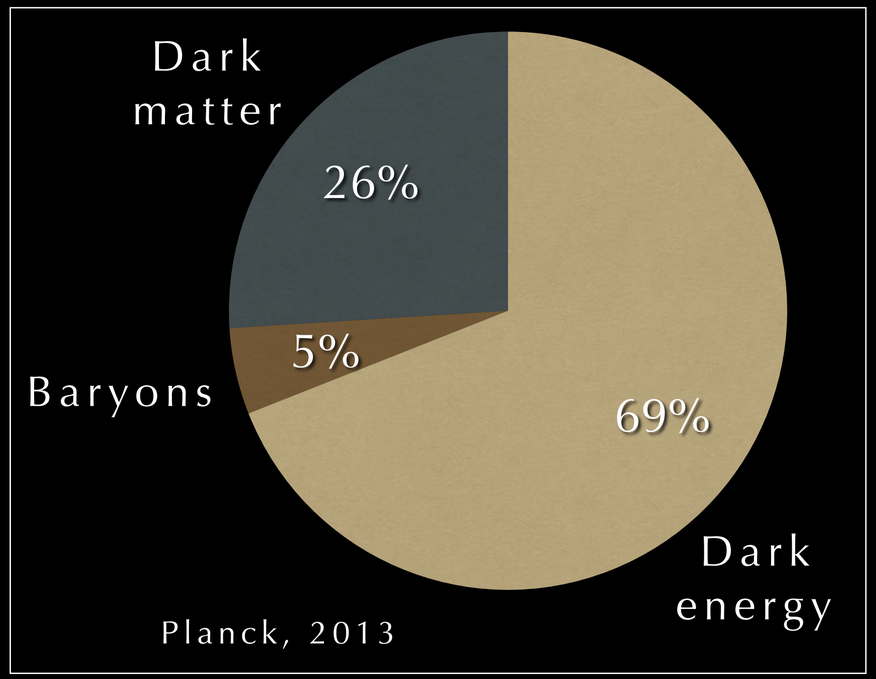
Focus of LLP Community has been signature-based rather than model-based from the beginning — what detector signatures are we overlooking or suboptimally covering? — and not as much on choosing benchmark models or model points to compare lines on plots

For dark showers, this requires some critical thinking...

What we talk about when we talk about dark showers

The SM is a bit complicated

Why would we expect the dark sector, with dark matter (DM) representing 5x the universal energy budget of baryons in the SM, to be *less* complicated?



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QCD

Dark QCD

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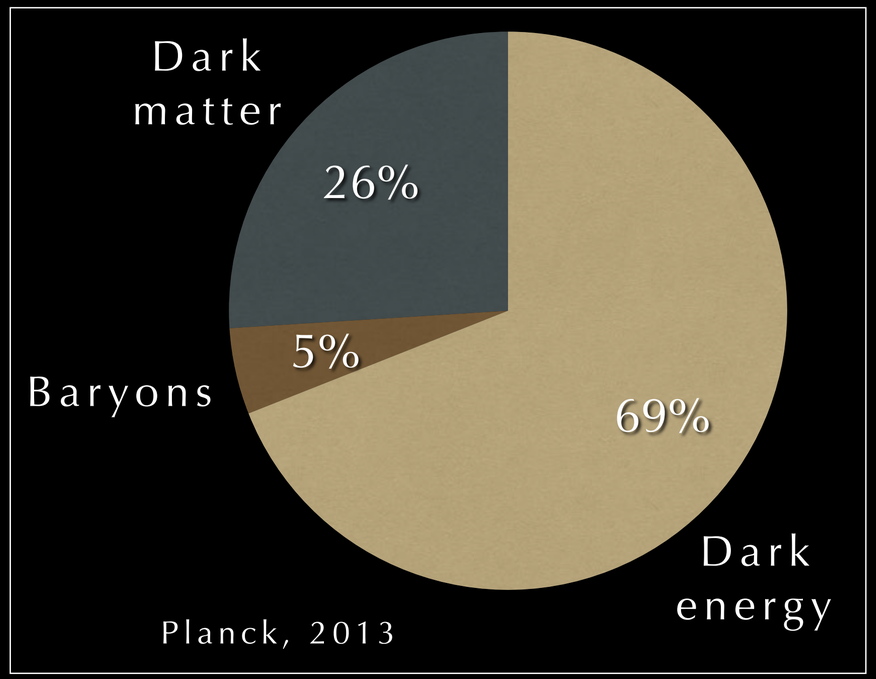

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But *how* similar to QCD?

QCD	Dark QCD
Non-abelian gauge theory	
SU(3) color gauge group	
Six flavors of fermions	
Color confinement at the ~100s of MeV scale which leads to hadronization and to objects known as *jets* at modern high-energy colliders	

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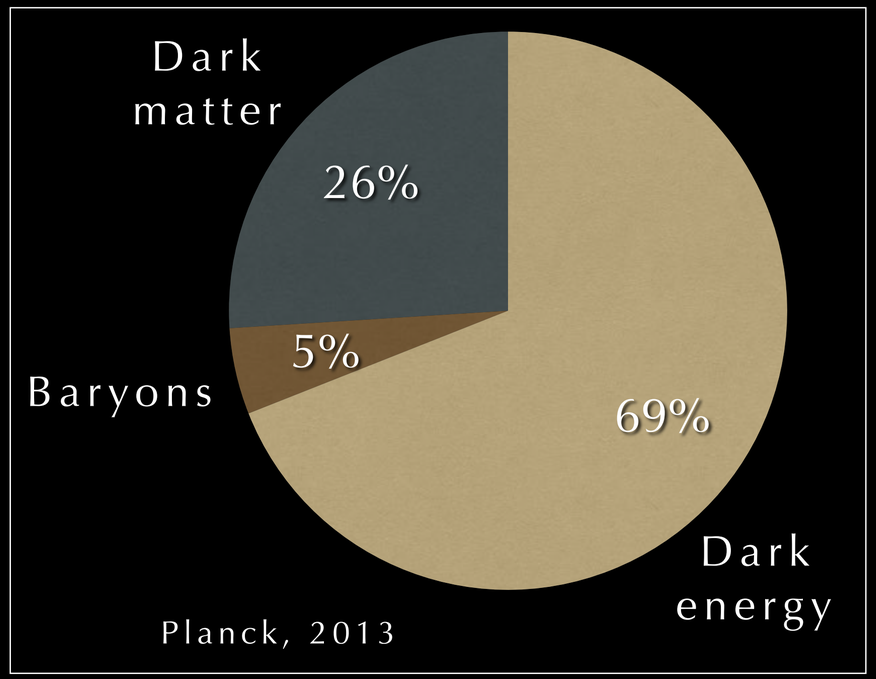

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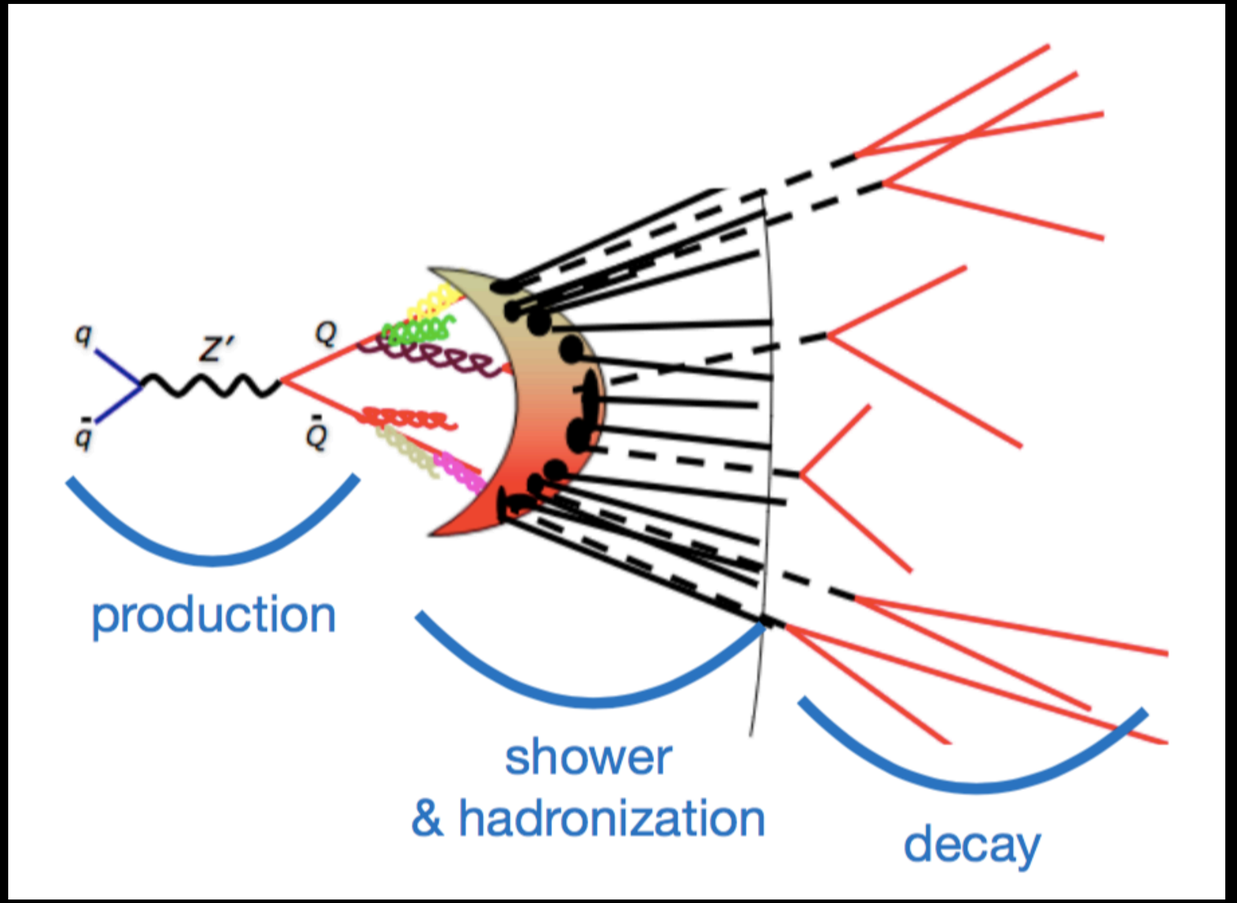
Non-abelian gauge theory	Non-abelian gauge theory?
SU(3) color gauge group	SU(?) color gauge group
Six flavors of fermions	? flavors of fermions
Color confinement at the ~100s of MeV scale which leads to hadronization and to objects known as *jets* at modern high-energy colliders	Color confinement? Scale? How strong? Jets? Soft radiation patterns? Something else entirely?

Anatomy of a dark shower

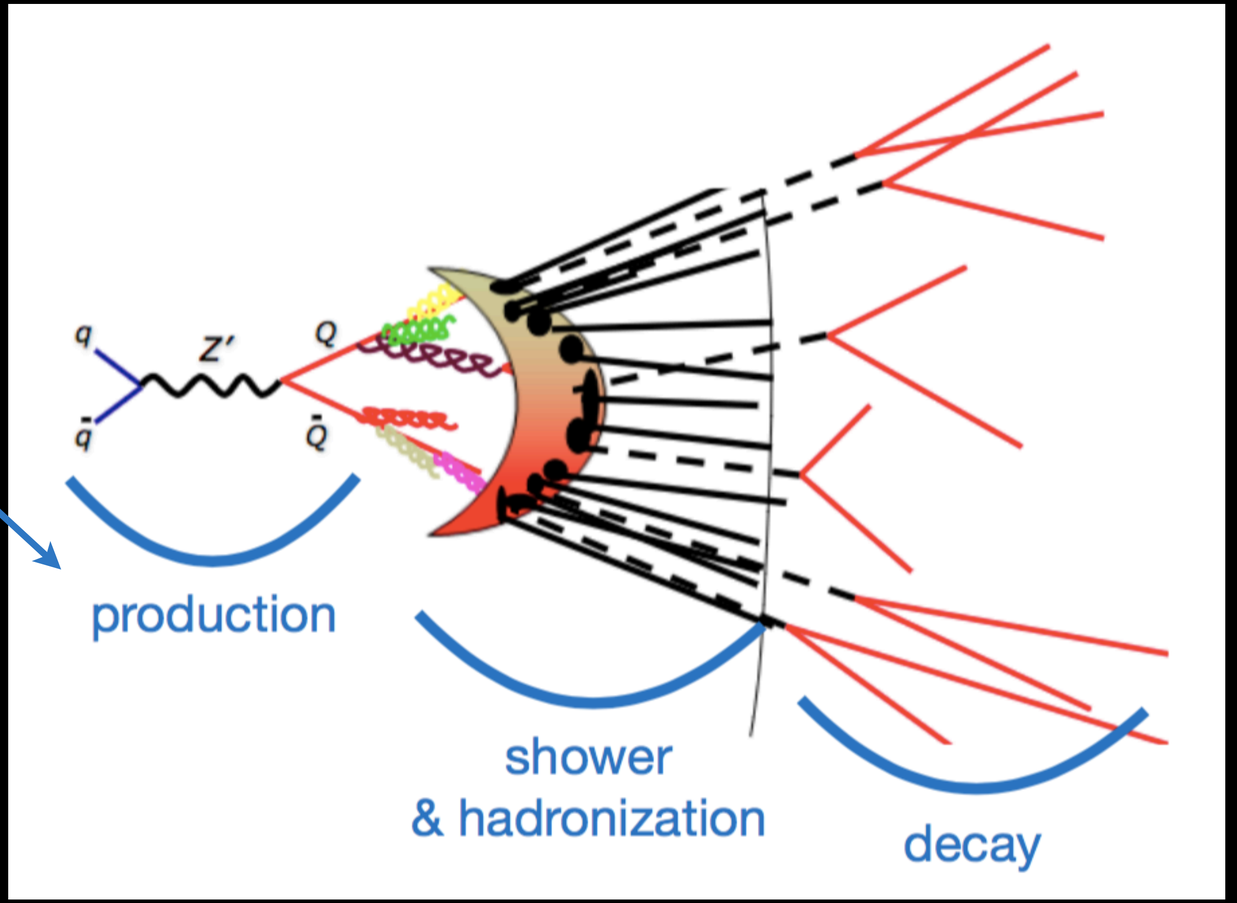


LLP Community white paper
[J. Phys. G 47 090501 (2020)], Chapter 7;
image adapted from M. Strassler

See S. Knapen talk from May 2019

Anatomy of a dark shower

1) Production of heavy state, e.g., Higgs, Z′, bi-fundamental scalar, etc., which decays into dark sector



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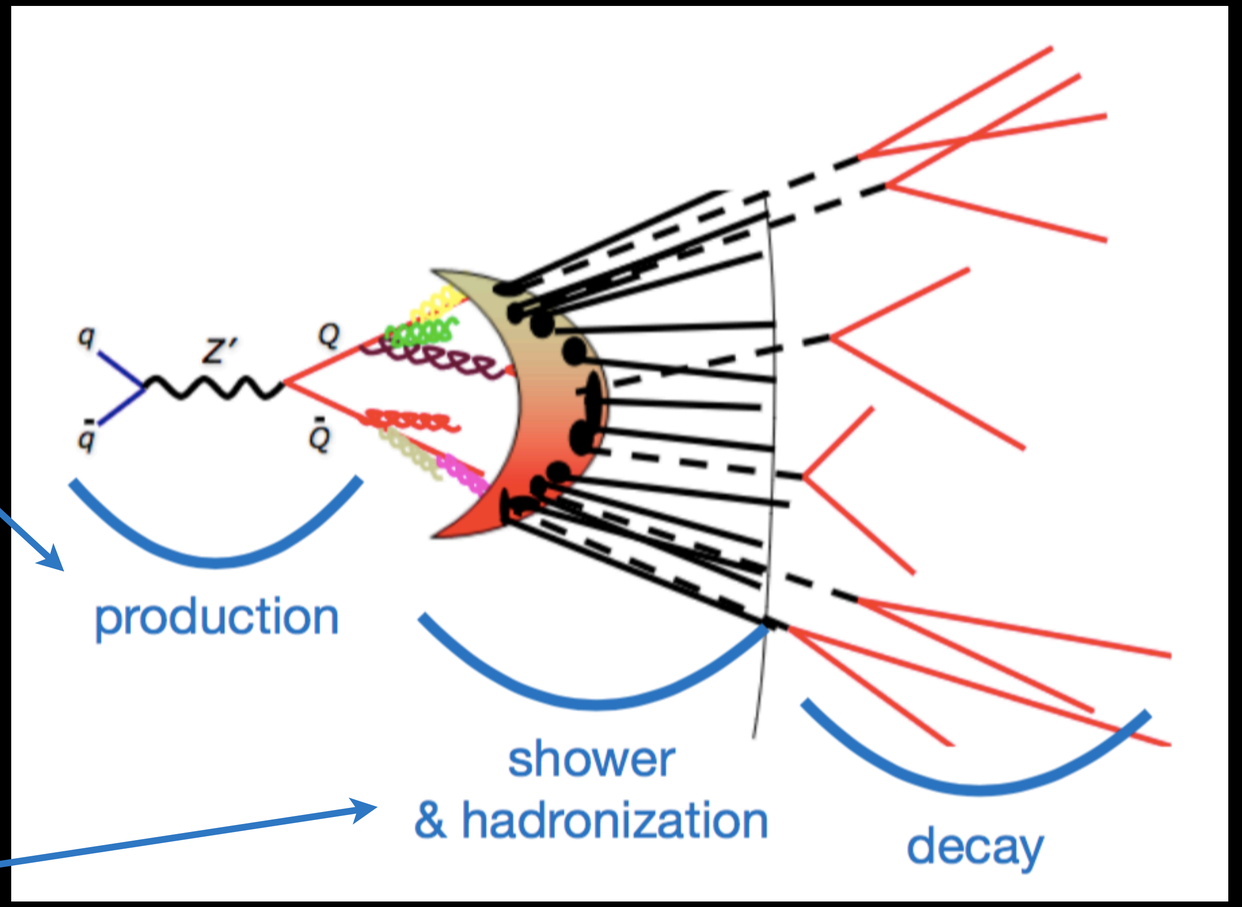
2) Depending on the coupling of the dark gauge group, dark states can shower and hadronize, leading to some kind of dark-sector jet, or a very soft radiation pattern, or something in between — *this part is the least well understood*



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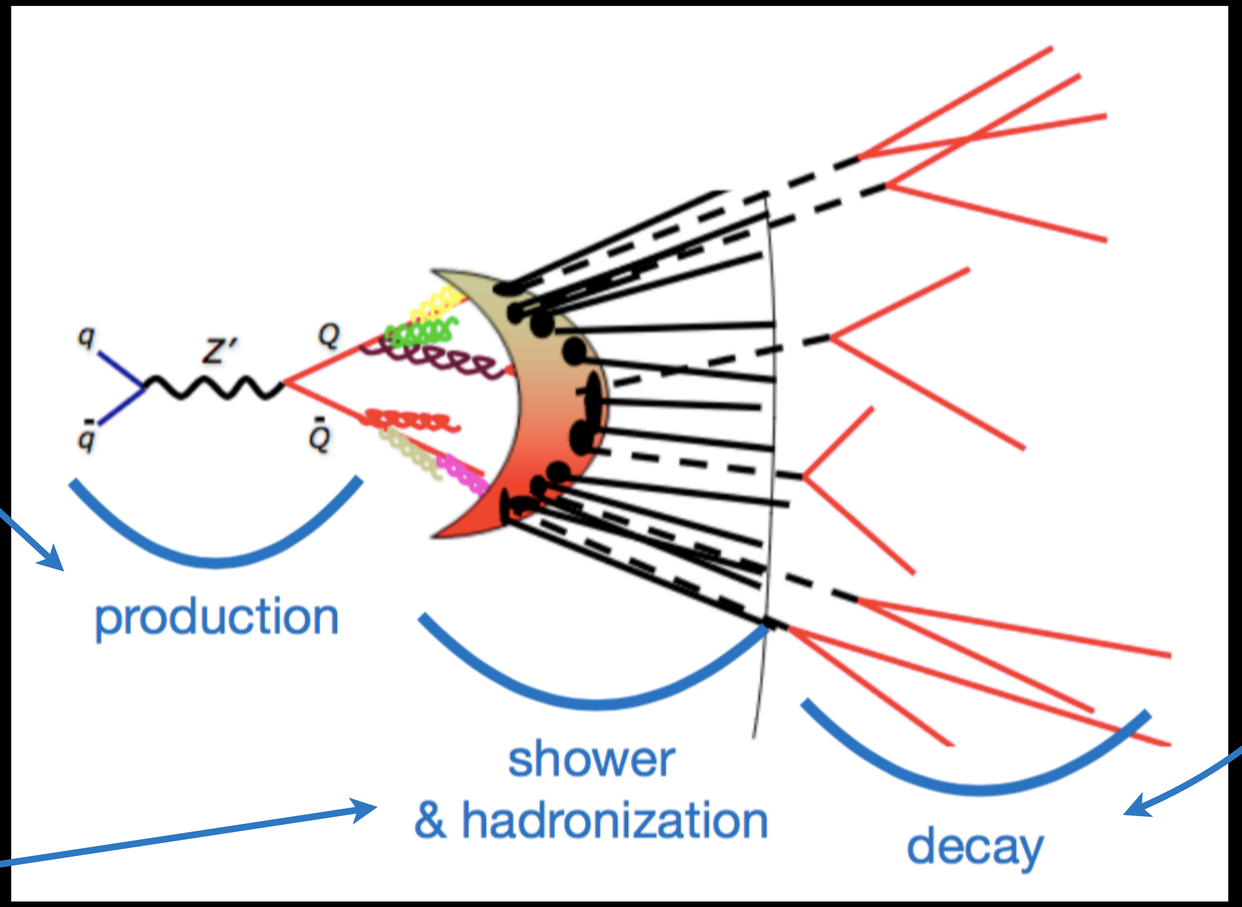

3) Dark sector hadrons (or equivalent) can decay back to the SM with a potentially wide range of lifetimes, pT spectra, etc.

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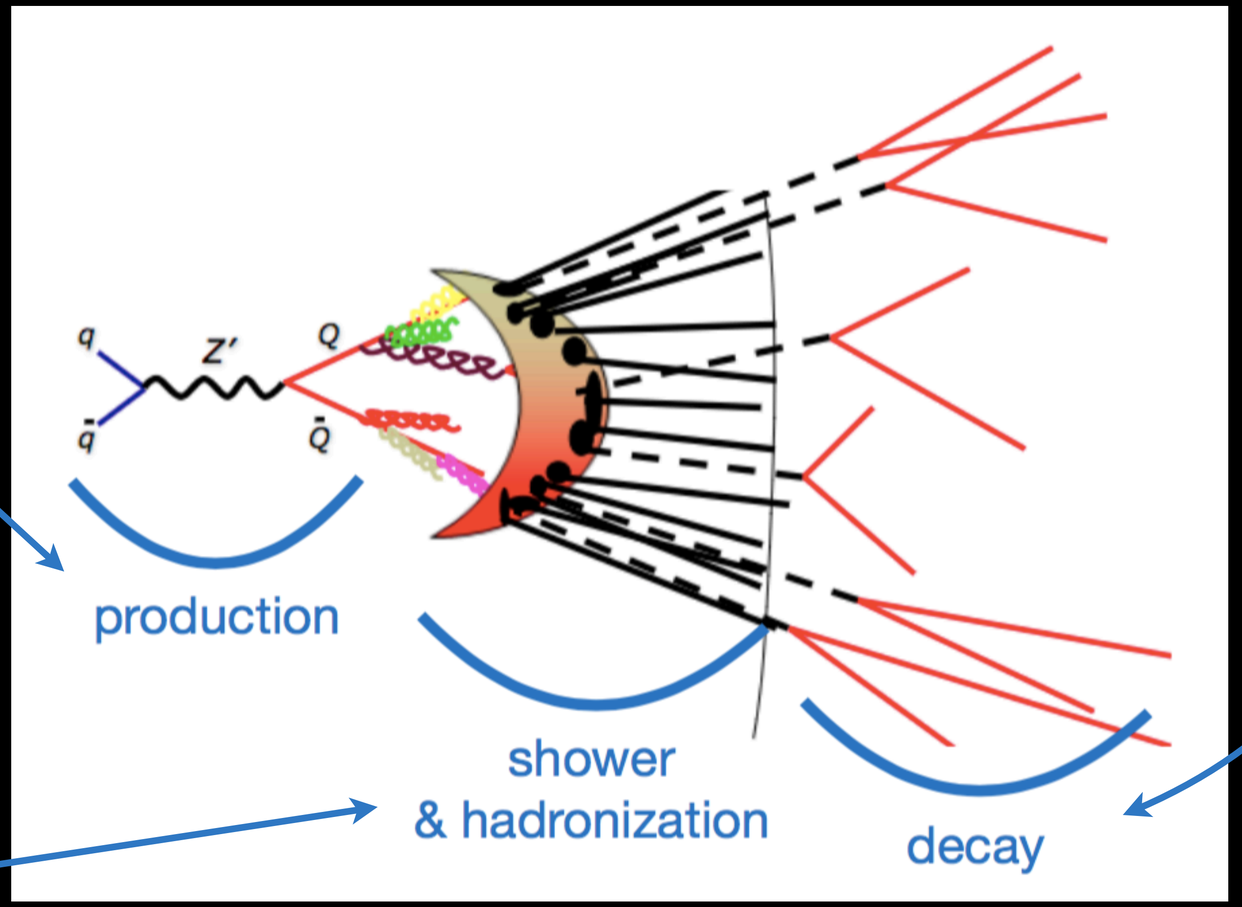

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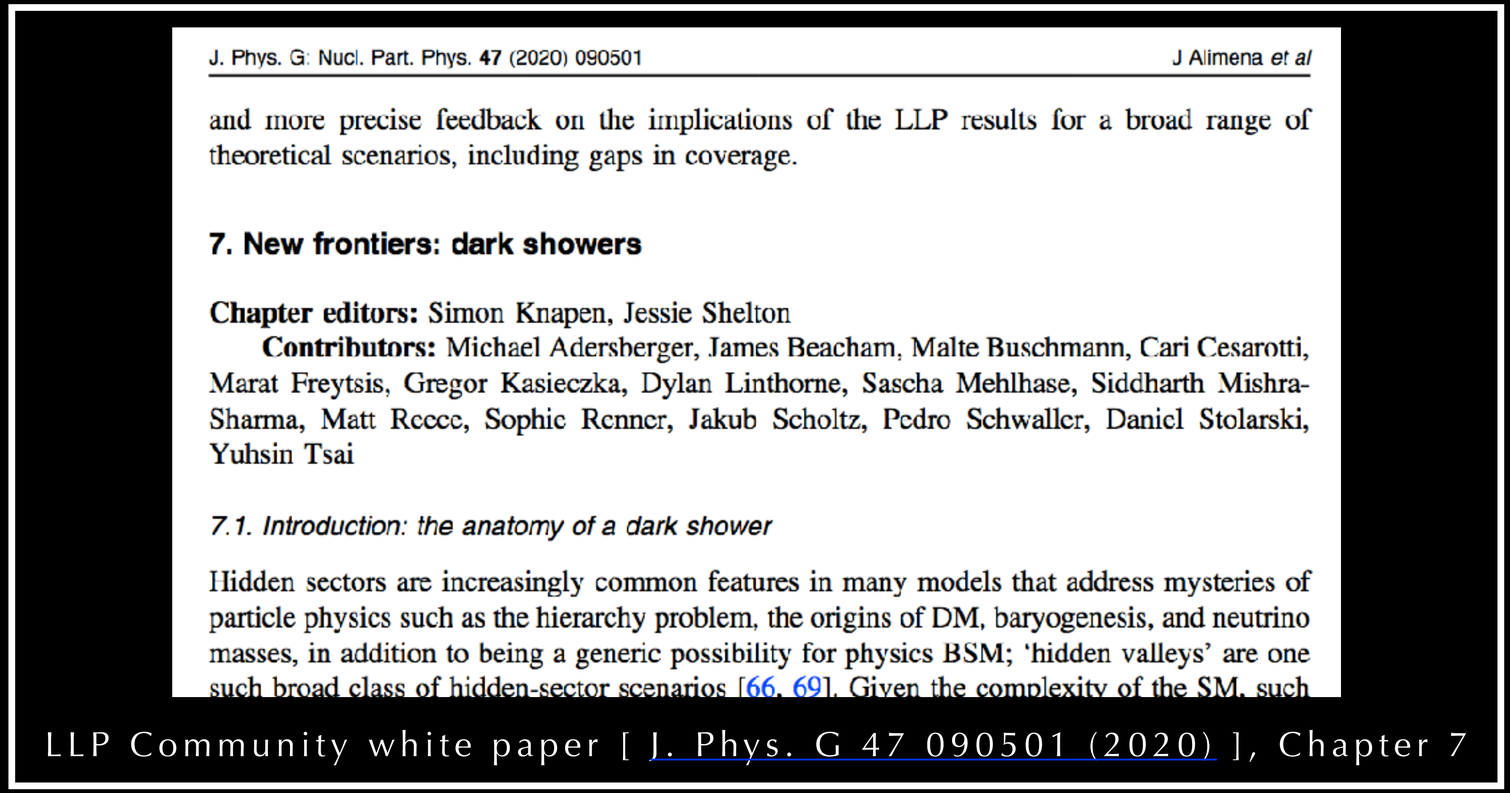
3) Dark sector hadrons (or equivalent) can decay back to the SM with a potentially wide range of lifetimes, pT spectra, etc.

Better understanding the range of event possibilities from 2) is essential to our ability to trigger on and catch dark showers at the LHC!

Dark showers: Ch. 7 of the LLP Community white paper

QCD-like (or -unlike) dark sectors underscore how much we don't know about what we don't know

Depending upon dark QCD gauge group, confinement scale, 't Hooft coupling, number of dark colors or flavors, production mechanism, and possibly unknown unknowns, we can potentially get very different signatures at high-energy colliders — most urgently at the LHC



and more precise feedback on the implications of the LLP results for a broad range of theoretical scenarios, including gaps in coverage.

7. New frontiers: dark showers

Chapter editors: Simon Knapen, Jessie Shelton

Contributors: Michael Adersberger, James Beacham, Malte Buschmann, Cari Cesarotti, Marat Freytsis, Gregor Kasieczka, Dylan Linthorne, Sascha Mehlhase, Siddharth Mishra-Sharma, Matt Reece, Sophie Renner, Jakub Scholtz, Pedro Schwaller, Daniel Stolarski, Yuhsin Tsai

7.1. Introduction: the anatomy of a dark shower

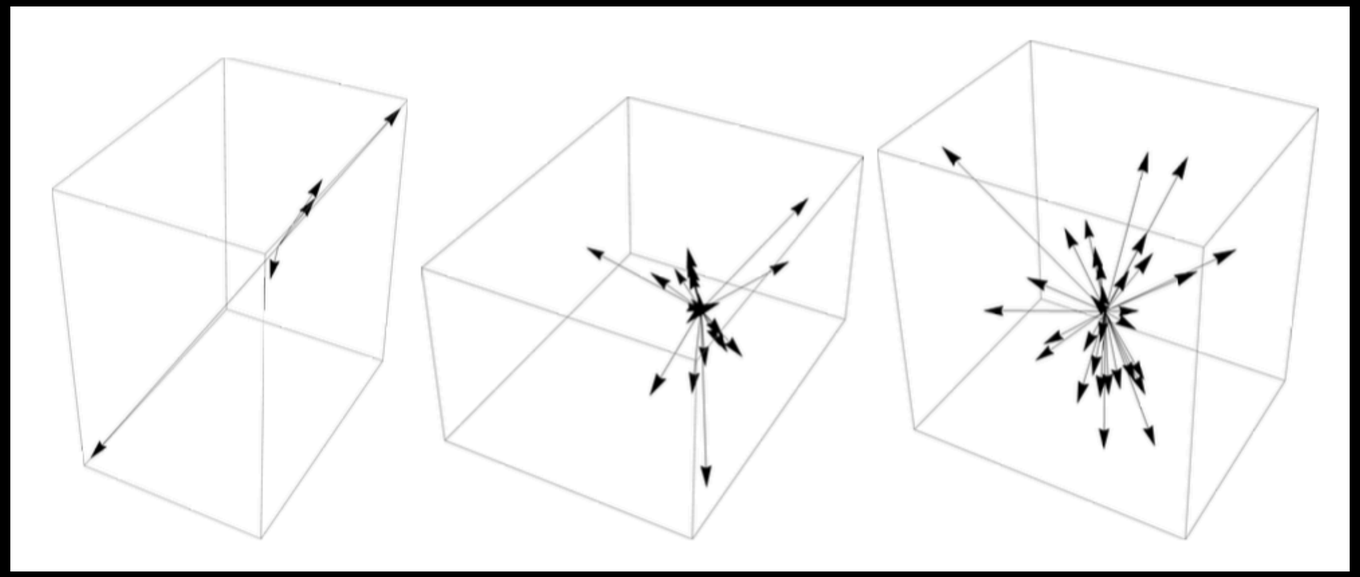
Hidden sectors are increasingly common features in many models that address mysteries of particle physics such as the hierarchy problem, the origins of DM, baryogenesis, and neutrino masses, in addition to being a generic possibility for physics BSM; 'hidden valleys' are one such broad class of hidden-sector scenarios [66, 69]. Given the complexity of the SM, such

LLP Community white paper [J. Phys. G 47 090501 (2020)], Chapter 7

Dark showers / dark QCD efforts within the LLP Community thus naturally and immediately gravitated toward the very non-understood parts:

1) How can we understand, from a theory perspective, the wide parameter space between weakly-coupled dark QCD (pencil-like jets similar to QCD) and strongly-coupled (quasi-spherical radiation patterns like SUEPs), the two regimes we understand at least partially?
2) How does the collider phenomenology change between these regimes?

Dark shower event shapes



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Dark shower event shapes

Jet-like; weakly-coupled; more like QCD

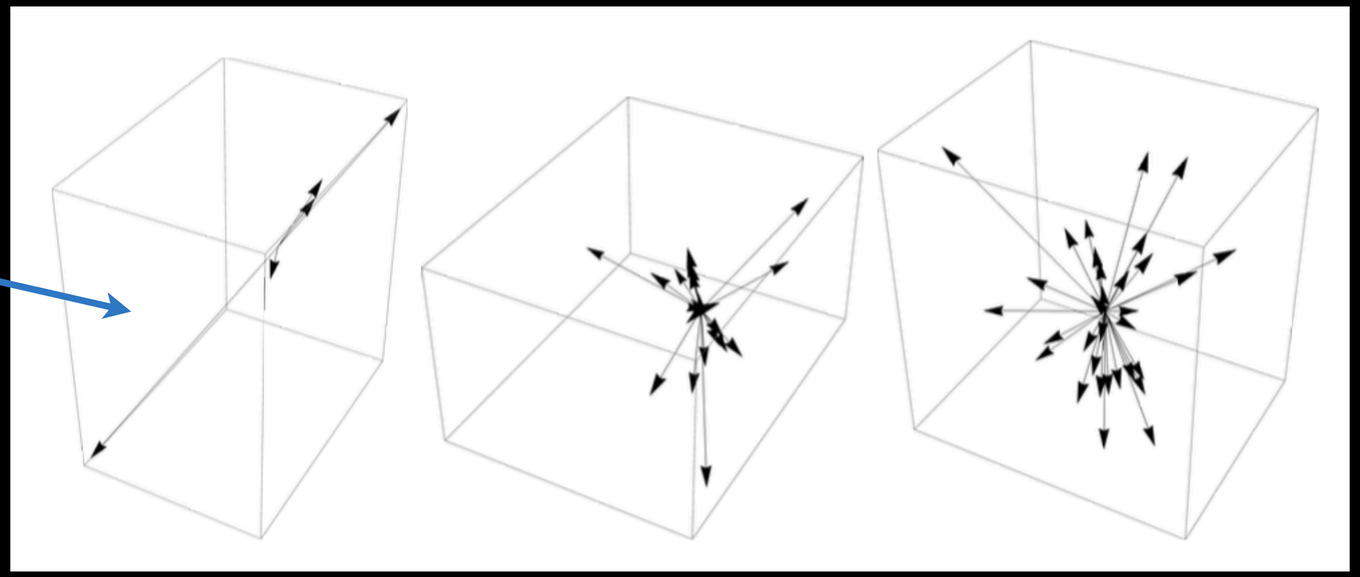
Since lifetime of the dark sector hadrons can and should be treated as a free parameter, this includes

Emerging jets
Semi-visible jets
Dark jets
Semi-displaced jets
Others

Perturbation theory works

Model with Pythia Hidden Valley module

Can trigger on at LHC



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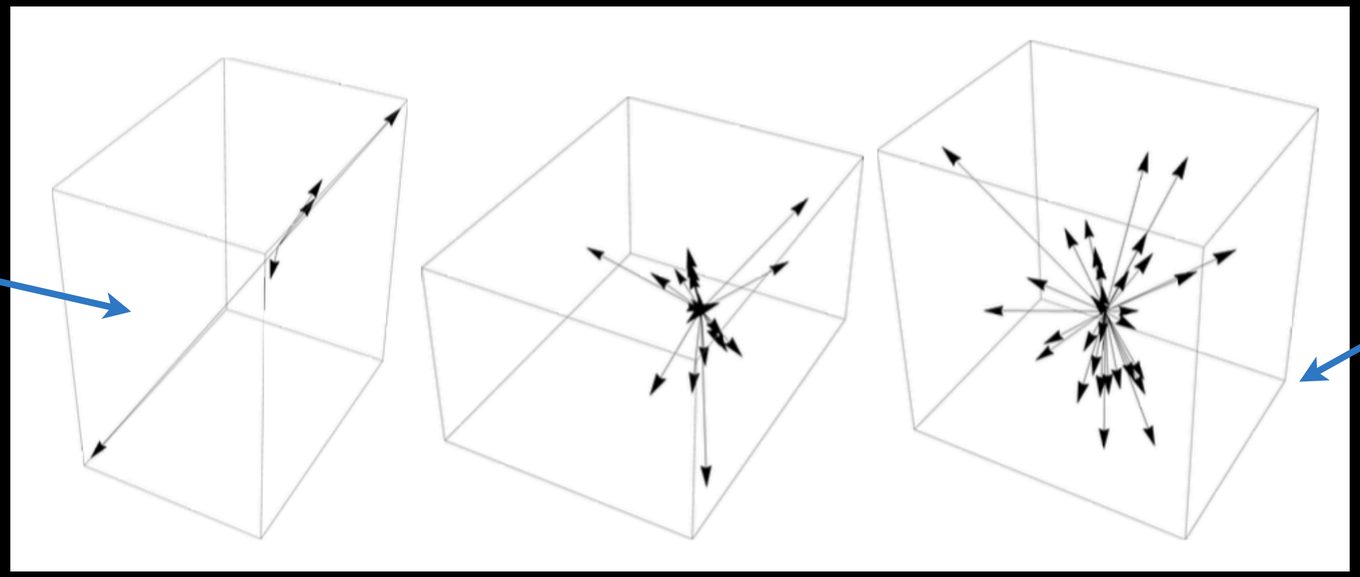

Spherical or quasi-spherical event shapes; strongly-coupled, less like QCD

SUEPs (soft, unclustered energy patterns), radiation patterns

Perturbation theory breaks down

Understand with gauge / gravity duality (AdS/CFT)

Modeled by S. Knapen

Can trigger on at LHC (in principle)

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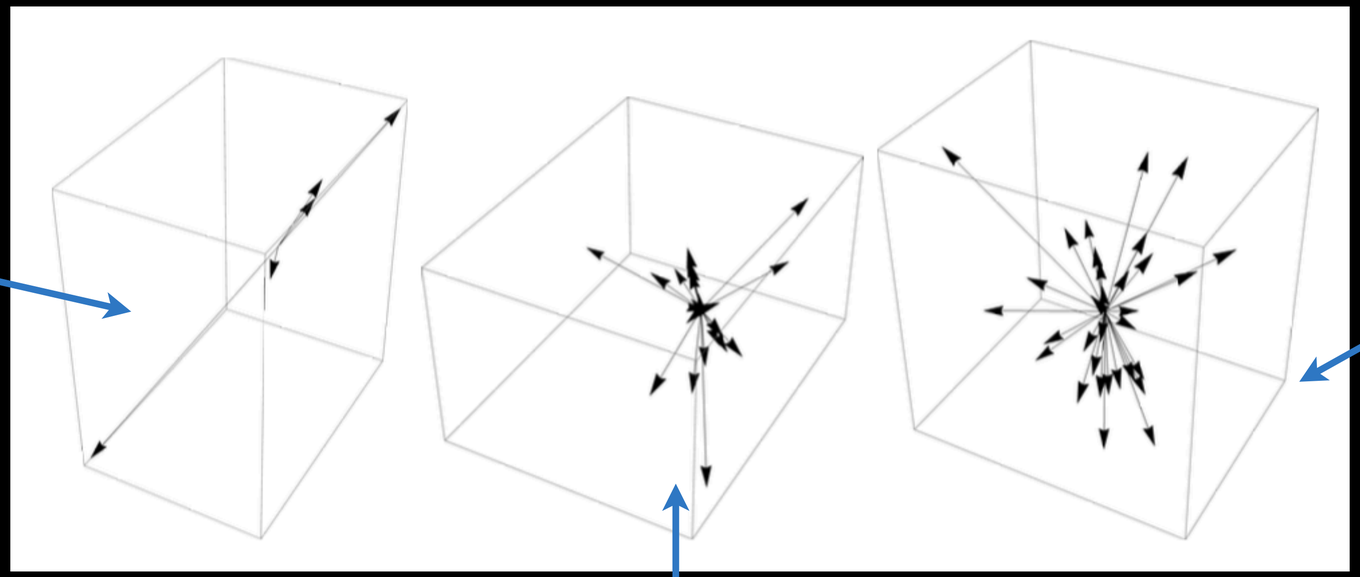

Intermediate regime — ???

This is the hard part, being worked on by C. Cesarotti, M. Reece, M. Strassler, M. Fretysis, others

Can try to extrapolate from both directions, "but strictly speaking, no overlapping regime of validity" (S. Knapen)

What does this look like at the LHC?

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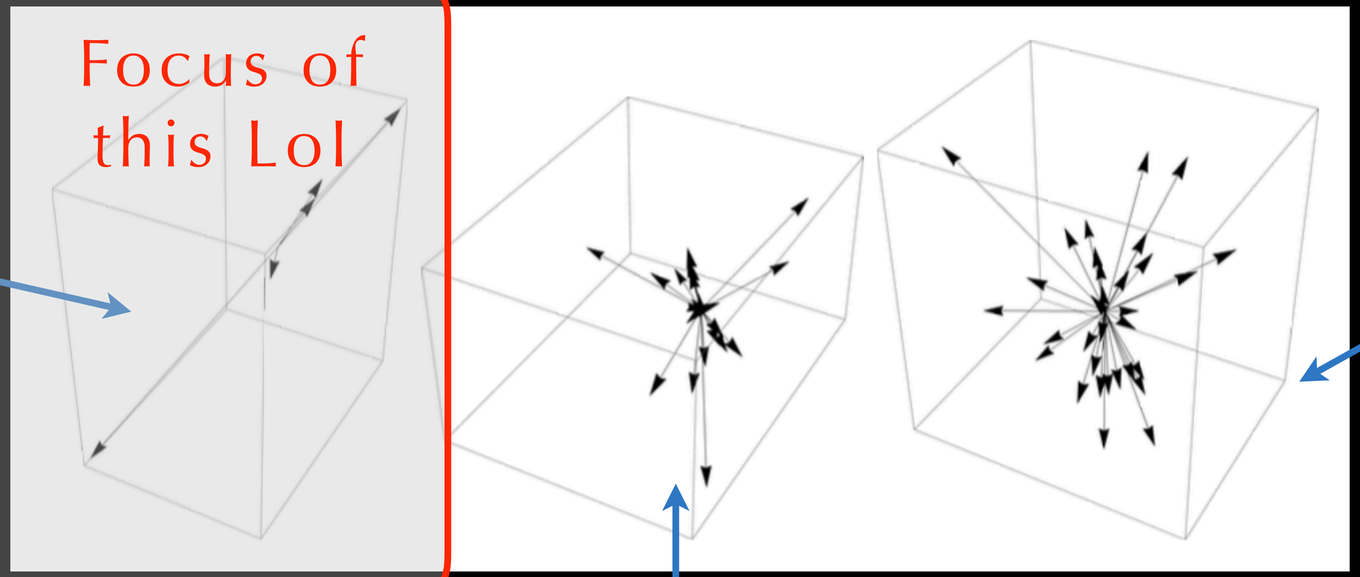
Focus of this LoI



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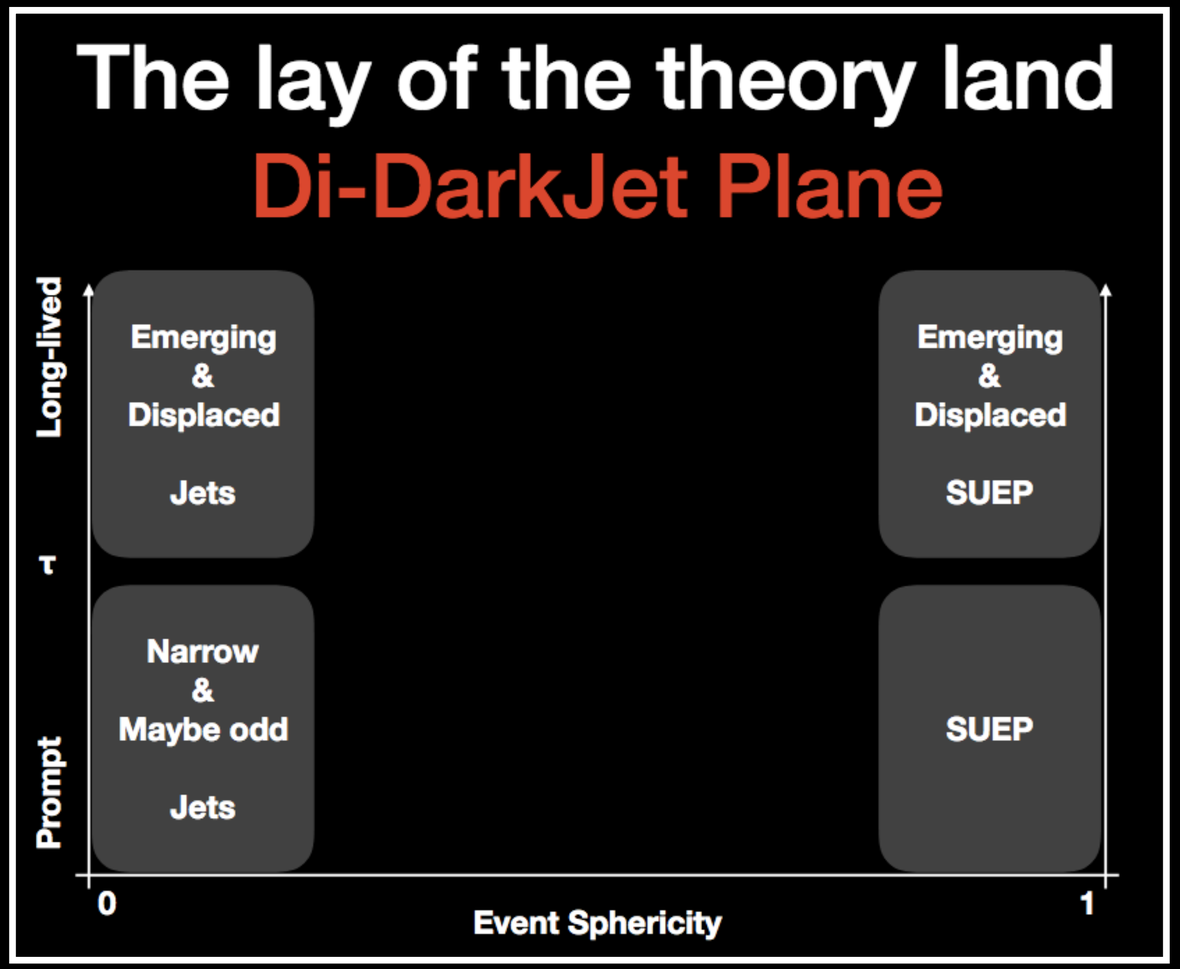
Dark showers and the LLP Community

Starting in 2016/7, convened a dark showers WG within the LLP Community initiative to think about these issue critically



J. Scholtz, dark showers WG talk, Oct. 2017 workshop

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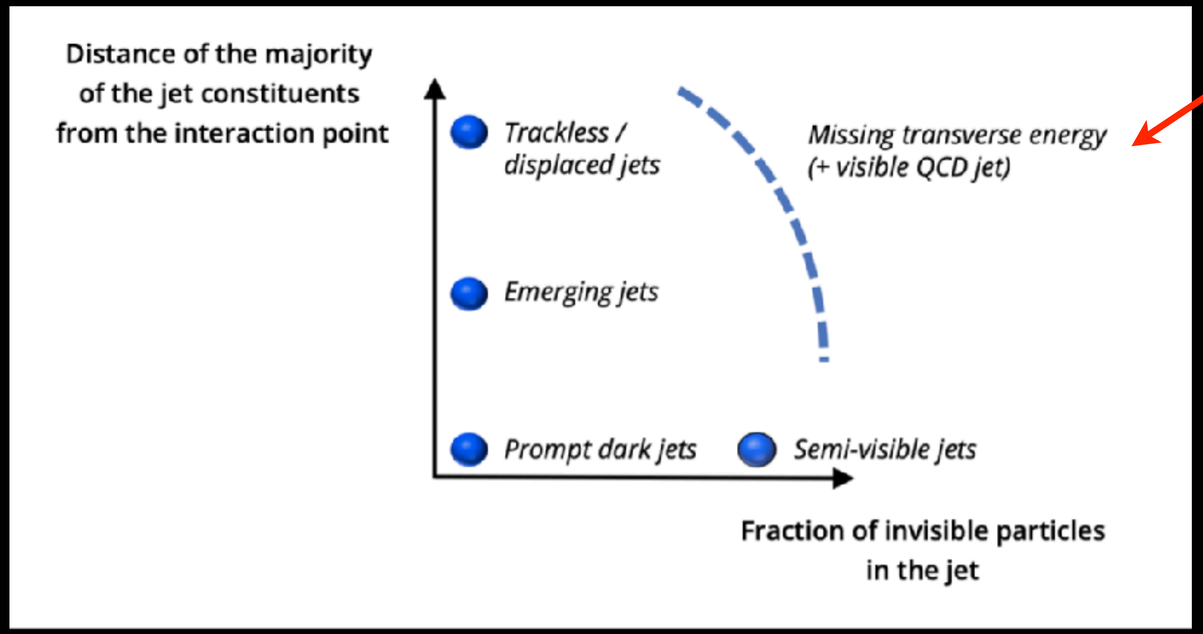
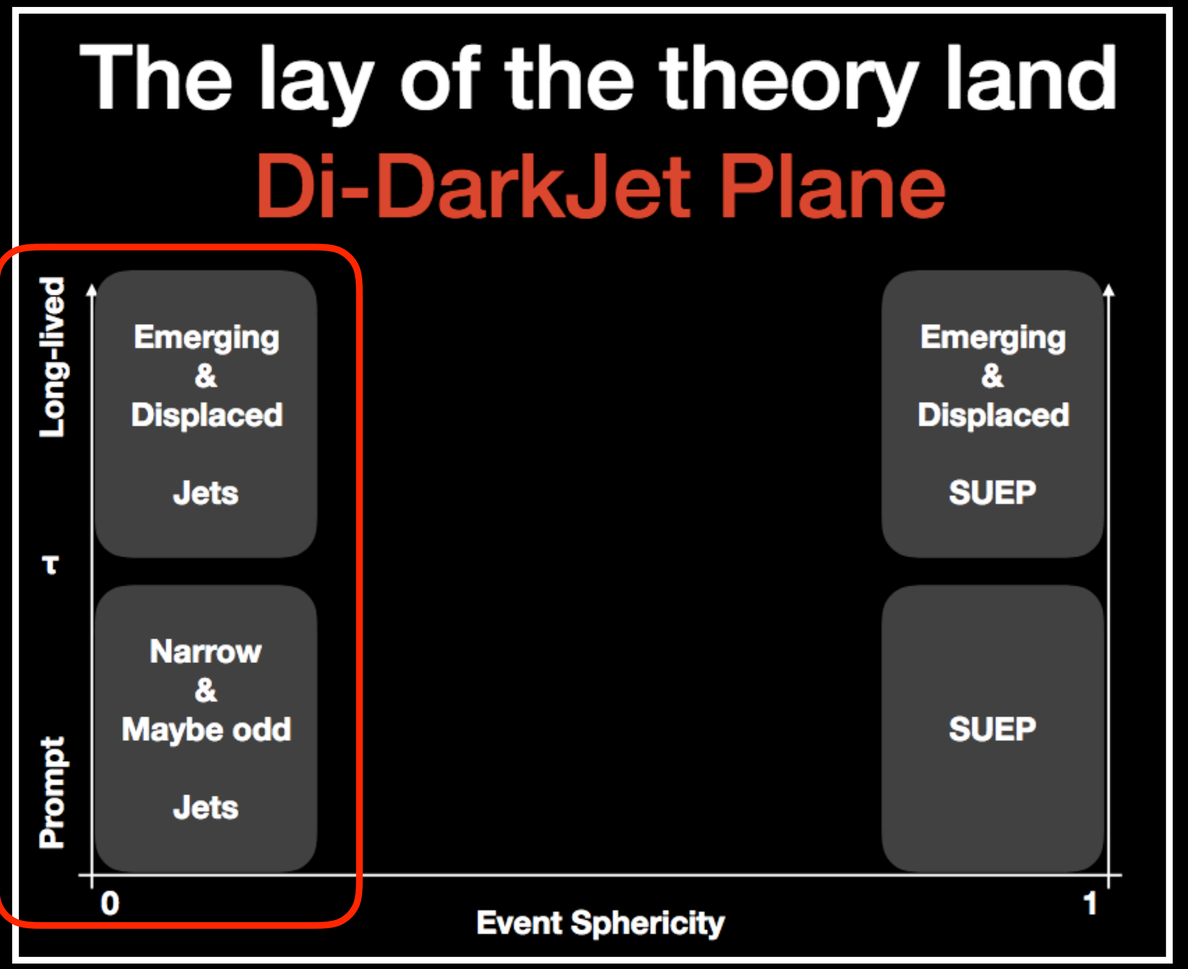
Complementary mindset
to that of the LoI





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Jet-like dark showers

When you're in the relatively-weak-dark-QCD-coupling (at high-energy colliders) regime, get a variety of signatures

Ingredients for (mostly) model-independent collider phenomenology

- Coupling that leads to jet-like objects
- High(-ish) multiplicity of low-mass dark hadrons that decay to SM
- Wide range of dark hadron lifetimes

Then can get

- Emerging jets — PRD 89, 063522 (2014), JHEP (2015) 2015: 59 (and CMS result: JHEP 02 (2019) 179)
- Semi-visible jets — PRL 115 (2015) 17, 171804; 1707.05326
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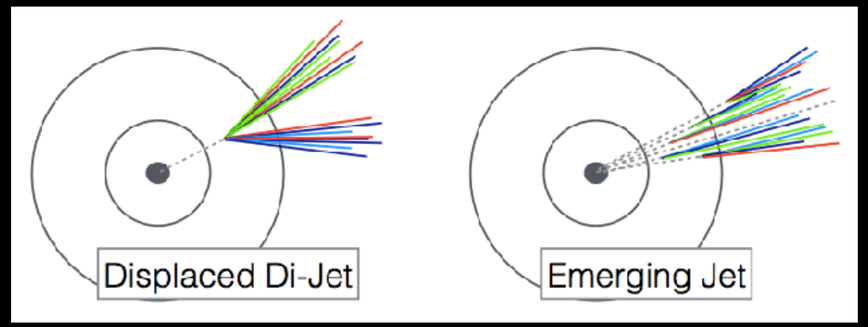

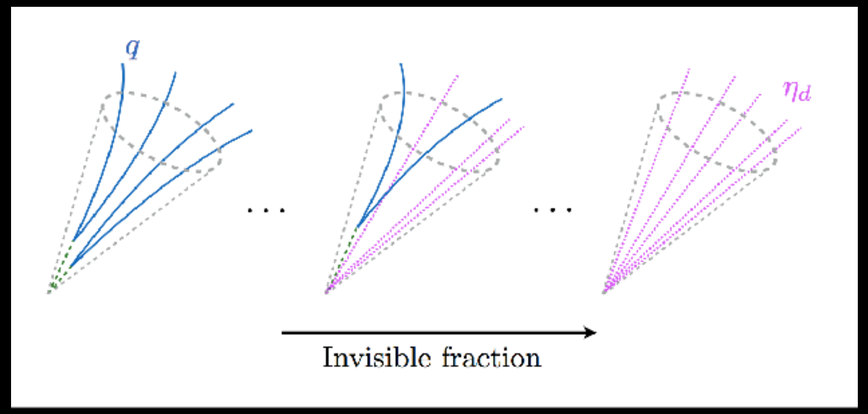

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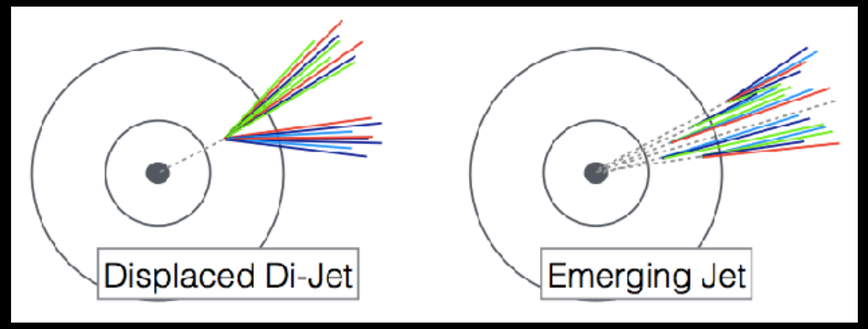

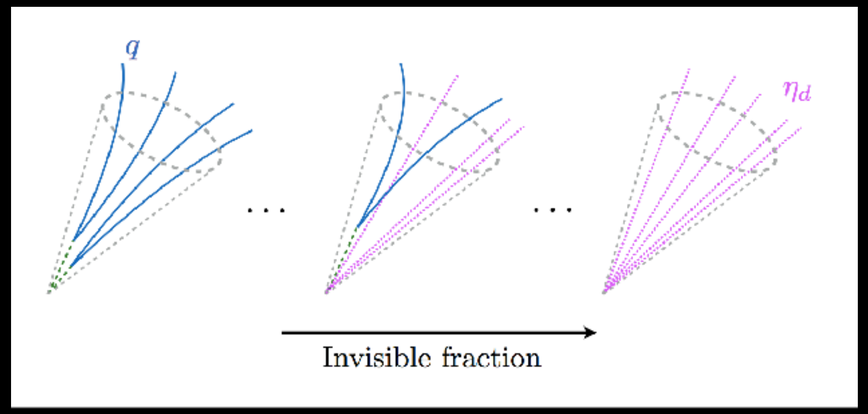

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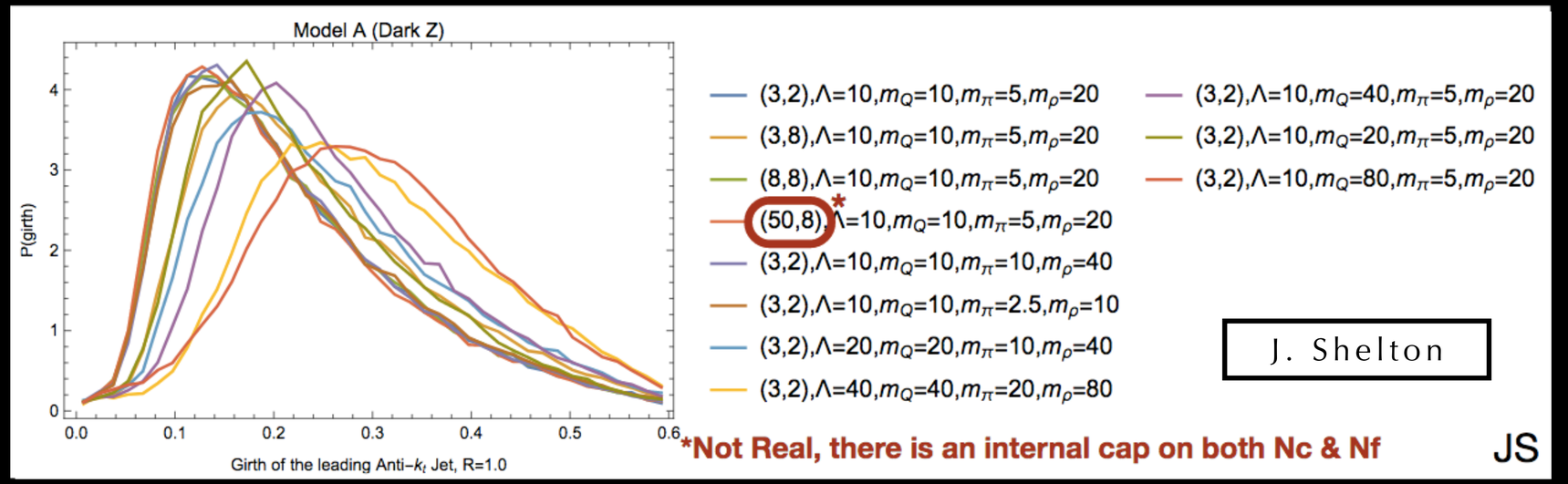
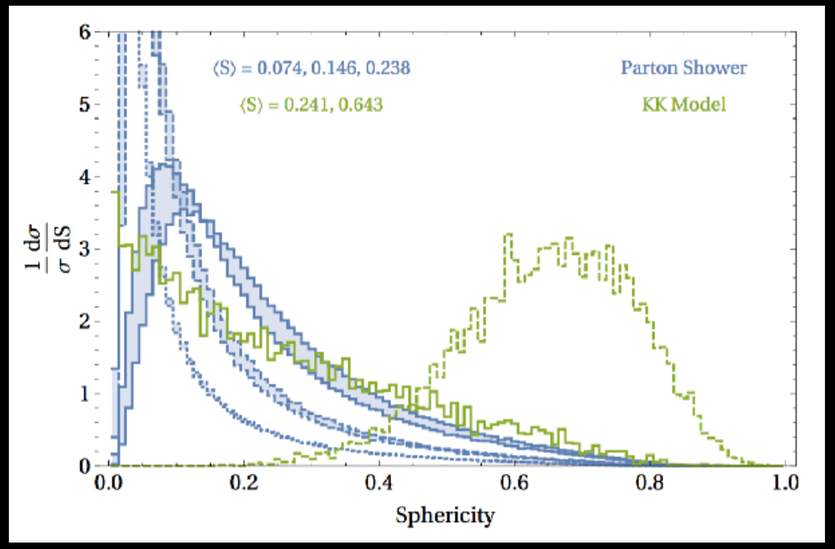
Even in the jet-like regime, this is a wide range of signatures and could certainly benefit from benchmarking

Pythia Hidden Valley and other MC

Effort within dark showers WG on understanding how changing Pythia Hidden Valley module parameters affects total event shape (from jets to, hopefully, SUEP)

Immediately found limitations in this direction





J. Phys. G 47 090501 (2020)

Also looked at VINCIA (which uses a dipole-antenna parton shower) instead of Pythia, to compare things like sphericity and thrust against an AdS/CFT-inspired model

NB: Current student work ongoing adjusting Nc and Nf in Pythia HV to look at event shapes, and potentially validate against QCD, because you may notice one thing...

Validating Pythia Hidden Valley

A Few Comments now about MCs

- If hidden physics is perturbative, MC will work
  - Feynman graphs
  - Perturbative showering
- If showering is perturbative and hadronization and hadrons are QCD-like
  - Rescaled/adapted PYTHIA/HERWIG/etc can work

That's what I did in HVMC and is what PYTHIA8 tries to do.

- But… Has anyone actually validated the PYTHIA8 Hidden Valley Module?
  - *I cannot vouch for it*
  - Does it reproduce QCD data where it should??
  - Watch out when $E / \Lambda < 25$ or so!

Meanwhile, if the hadron spectrum is quite different from QCD

- If it's just $N_f>1$ pseudoscalar mesons, can probably work out what happens,
  - but someone has to do it and then **put it into the MC**
- If it's the $N_f=1$ case, can't be precise about how hadronization makes mesons
- If it's the $N_f=0$ case, or some other case, it's much worse…

M. Strassler talk, May 2018 workshop

M. Strassler pointed out that, as of May 2018 and to his knowledge, no extensive validation studies of Pythia8 Hidden Valley module

If this has been done since then, I'm happy to be informed!

But seems like a first-order task to perform before choosing dark showers benchmarks using this module

Dark showers: Talks at May workshop

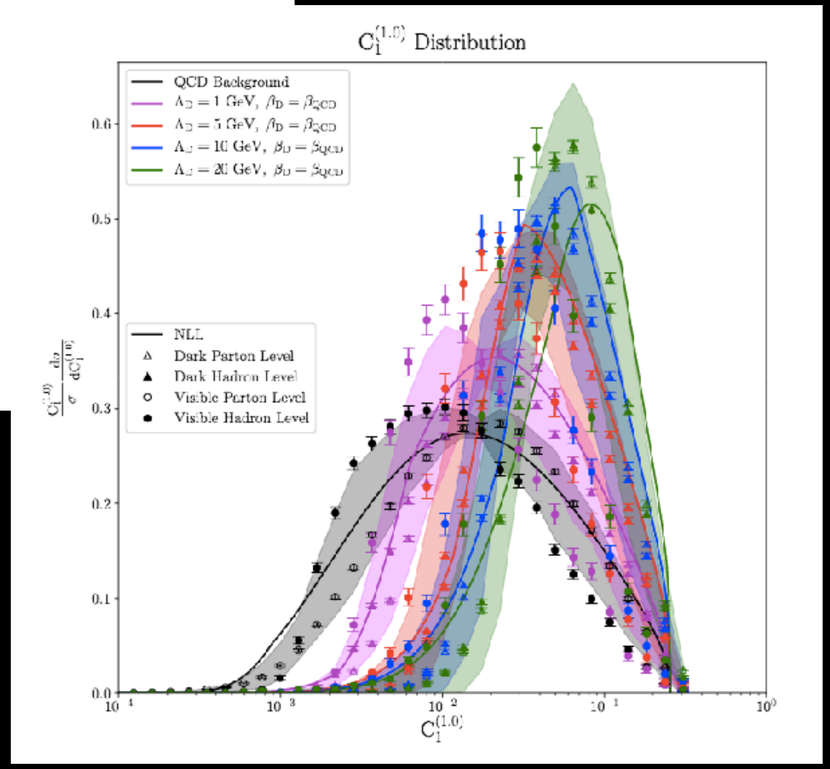
17:25 **Casting a ParticleNet to catch dark showers**
Speaker: Elias Bernreuther (RWTH Aachen University)
ml_darkshowers.pdf

17:40 **Challenges of searching for low mass LLPs from strongly interacting dark sectors**
Speaker: Patrick Tunney (King's College London)
LLP_SIMP.pdf

17:55 **Discussion**

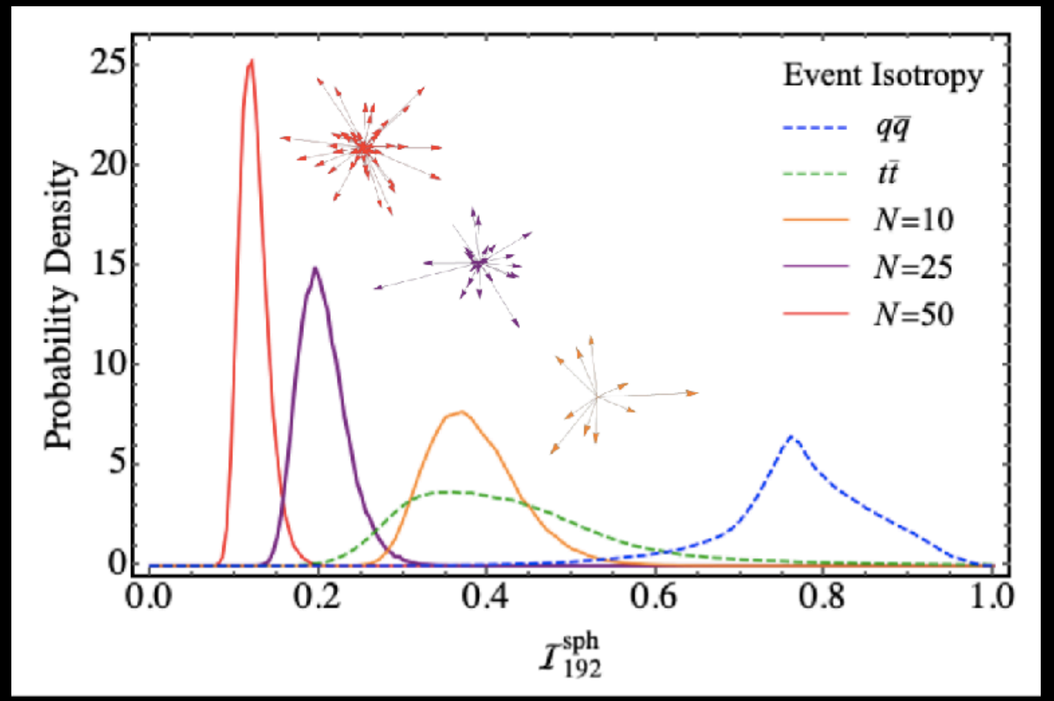
18:10 **Dark showers with jet substructure**
Speaker: Dr Marat Freytsis (Rutgers University)
LLPVirt0520.pdf

18:25 **A robust measure of event isotropy at colliders**
Speaker: Cari Cesarotti (Harvard University)
LLPisotropyCesarot...



M. Freytsis talk, May 2020 workshop

Relevant for this LoI is the recent work by Cohen, Doss, Freytsis examining the effect of modeling uncertainities on jet substructure variables that could distinguish between QCD and dark (prompt) jets



Recent work (some initially developed within the LLP Community) by C. Cesarotti, J. Thaler (2004.06125) and Cesarotti, M. Reece, and M. Strassler (2009.08981) to phenomenologically interpolate between jets and SUEPs with a new event-shape observable, event isotropy (see also Cari's talk)

Dark showers: Plans for November workshop

November workshop will be virtual again

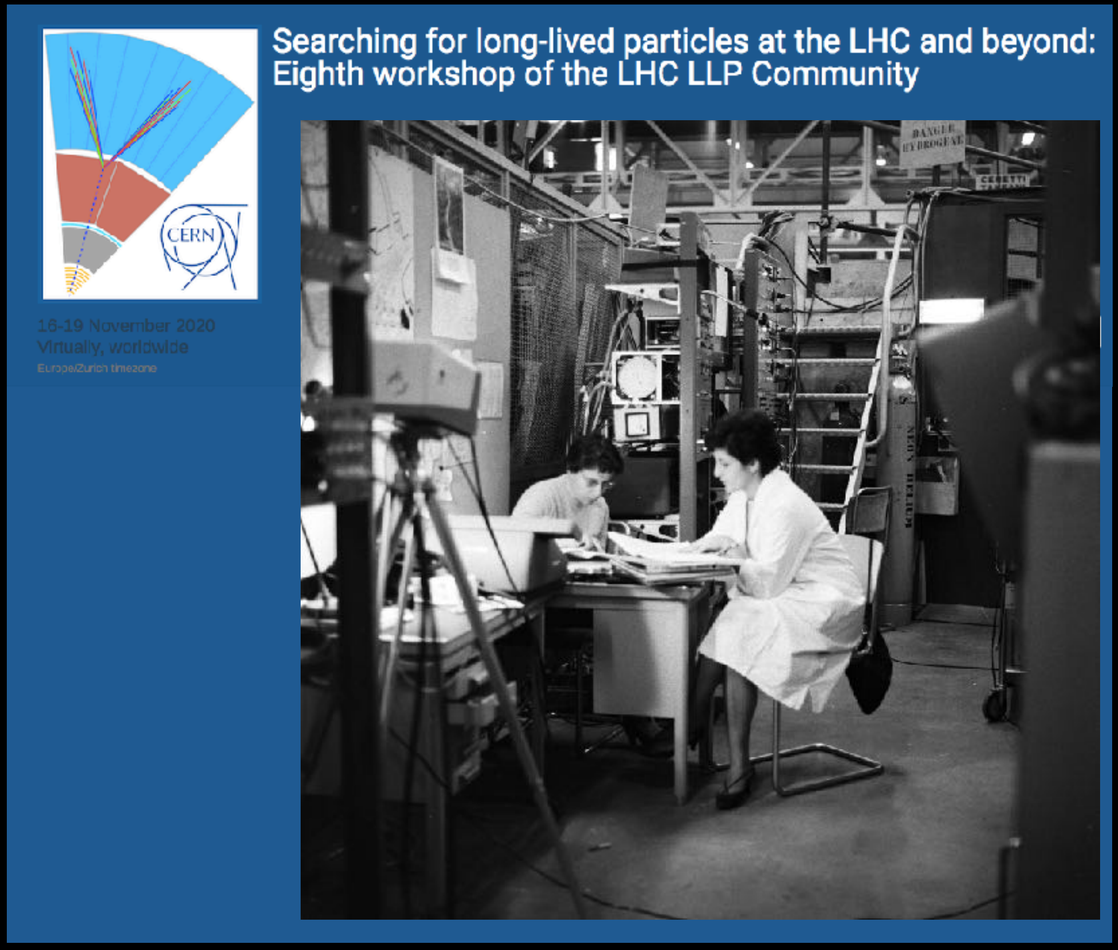
Registration and call for abstracts open

https://indico.cern.ch/e/LLP_Nov_2020

Organized more around virtual working groups rather than a series of talks, as in May

Dark showers WG session (coordinated from the organizers' side by K. DiPetrillo and me) will likely address some subset of the following topics (or others):

- Benchmarking (*related to this LoI*), for jet-like objects and potentially intermediate regime
- Event isotropy and energy-mover's distance
- Simulation (ways to include event isotropy interpolation approach into, e.g., SUEP code?)
- Dark showers meet astrophysics (*related to this LoI*)
- Your idea goes here



Conclusions

The prospect of discovering dark showers / dark QCD is exciting but also underscores how much we don't know about what we don't know

Benchmarking the jet-like regime could be greatly beneficial

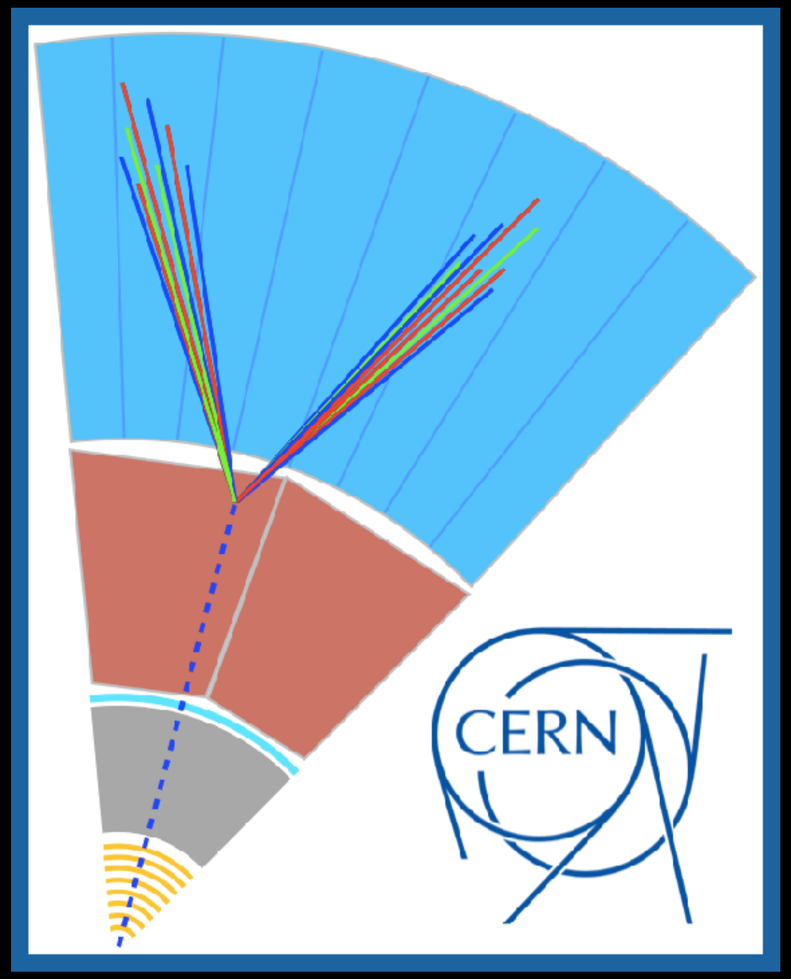
LLP Community dark showers WG happy to collaborate!

Some dark showers references, very non-exhaustive

Classic hidden valley literature — PLB 651:374-379, 2007; JHEP 07 (2008) 008, others
Emerging jets —PRD 89, 063522 (2014); JHEP (2015) 2015: 59; JHEP 02 (2019) 179
Semi-visible jets / dark jets — PRL 115 (2015) 17, 171804; 1707.05326
Soft, unclustered energy patterns (SUEPs) — JHEP (2017) 2017: 76
Recent work — 2004.06125; 2009.08981; 2004.00631, others

Most comprehensively in "New Frontiers: Dark showers", Chapter 7 of the LLP white paper — J. Phys. G 47 090501 (2020) — and copious references therein

Reserve slides



LHC Long-Lived Particle Community

...in collaboration with the theory/pheno community and MoEDAL, MilliQan, MATHUSLA, FASER, CODEX-b, AL3X, ANUBIS, CLIC/ILC, FCC/CEPC, SHiP, NA62, NA64, etc.

Formed in 2016 to address one question:
How do we best ensure that we don't miss BSM LLP signatures for the remainder of the LHC program?

Workshops — two per year

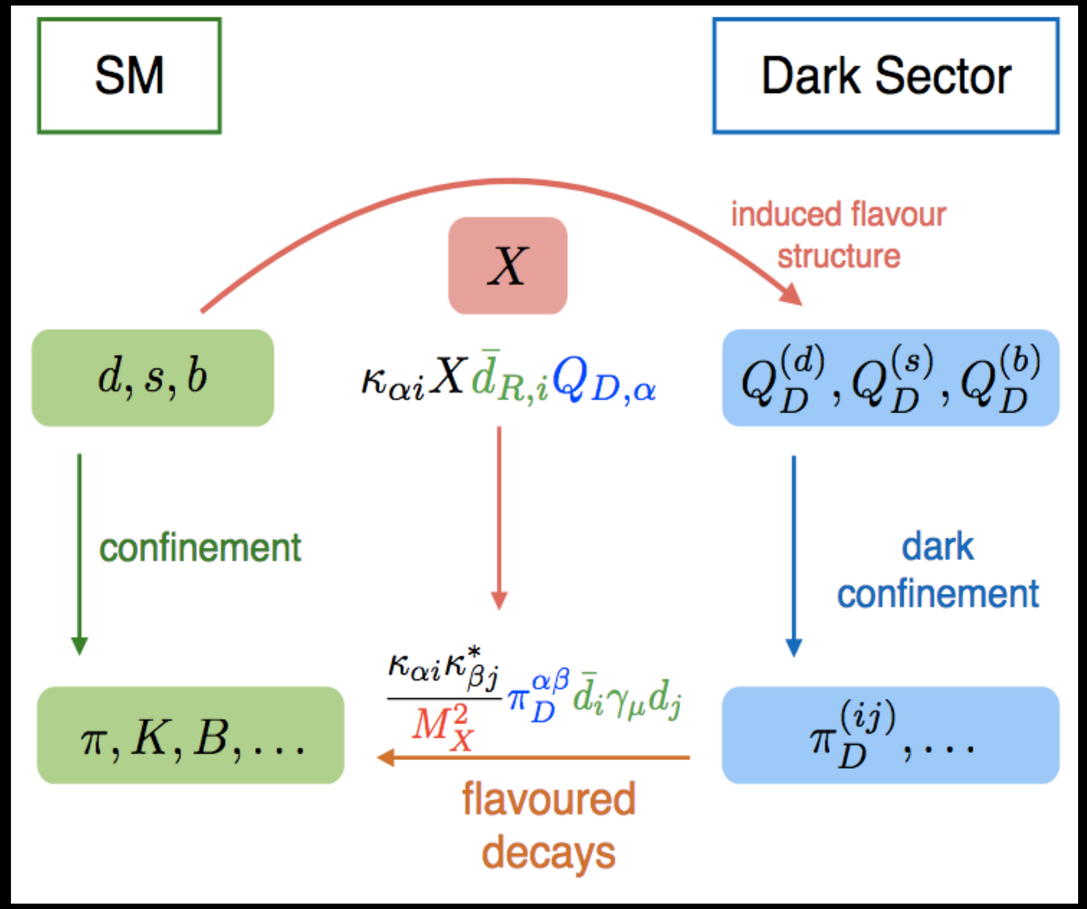
LHC LLP white paper:
Public March 2019 — J. Phys. G 47 090501 (2020)

Join the CERN egroup: lhc-llp

cern.ch/longlivedparticles

Jet-like dark showers: Emerging jets

Dark sector needs to eventually talk to the SM, or all hope is lost



S. Renner

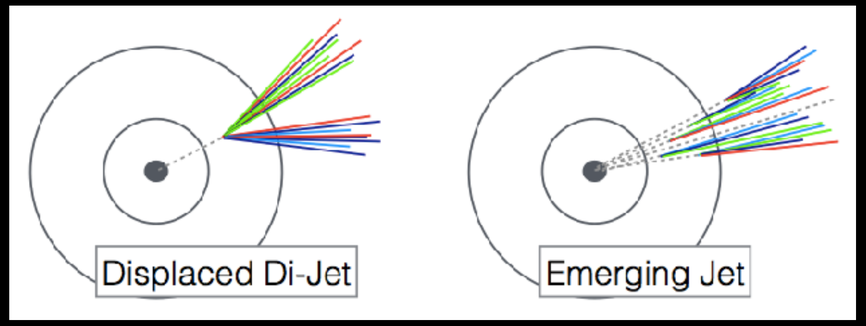
This can be achieved with a dark QCD with TeV-scale mediator X_d that communicates with both the dark sector and the SM and GeV-scale Q_d

- Bai, Schwaller PRD 89, 063522 (2014)
- Stolarski, Schwaller, Weiler JHEP (2015) 2015: 59

New matter is introduced such that QCD and dark QCD confinement scales are near each other at the GeV scale

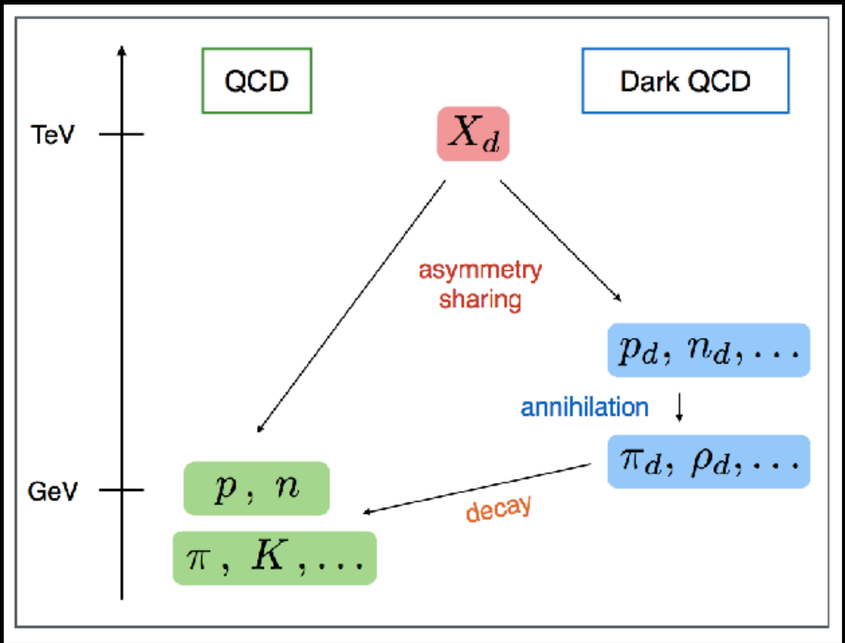
- Leads to desired asymmetry
- Also implies new matter must be charged under both dark QCD and SM QCD
- Leads to potentially discoverable phenomenology: Dark hadron zoo (including a stable DM candidate, a dark proton), similar to QCD, some of which must decay back to the SM

Jet-like dark showers: Emerging jets

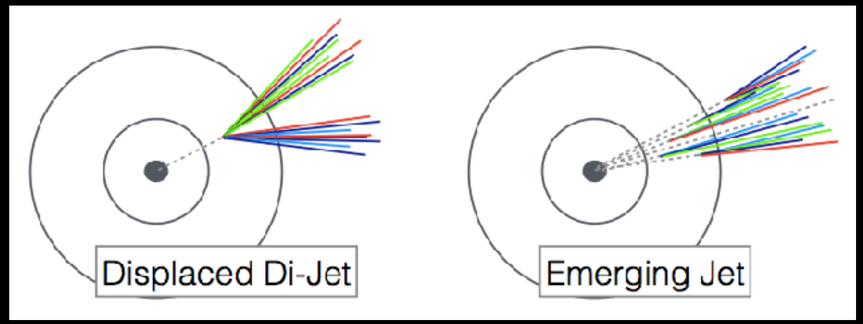


Jet-like dark showers: Emerging jets

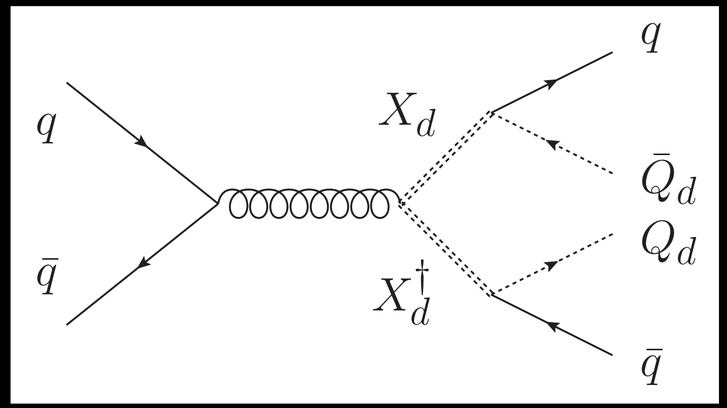
JHEP (2015) 2015: 59



Dark quarks hadronize first in the hidden sector and, e.g., long-lived dark pions then decay to the visible sector via multiple displaced vertices of varying displacements within the same jet object

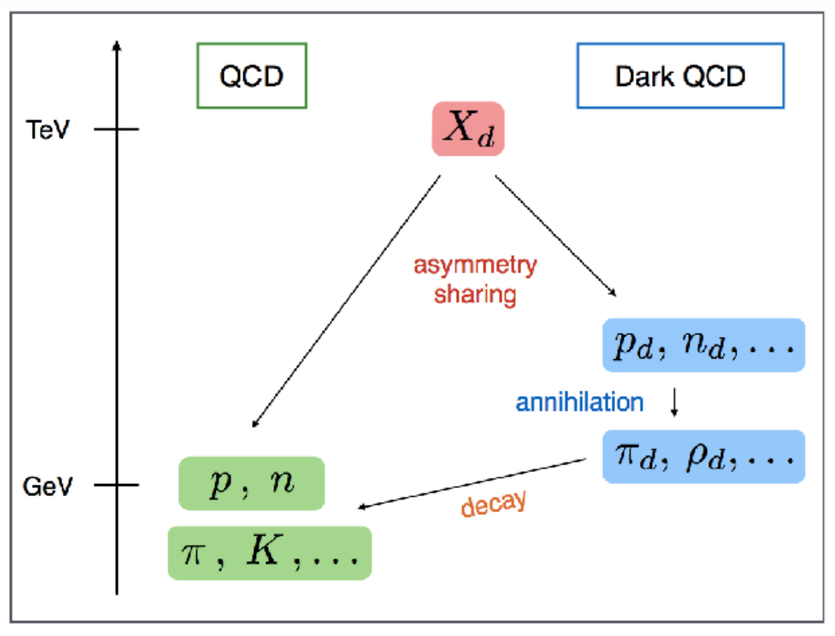


Thus, this is **neither prompt jets nor a pair of displaced jets** pointing to the same displaced vertex, but **emerging jets**



Jet-like dark showers: Emerging jets

JHEP (2015) 2015: 59



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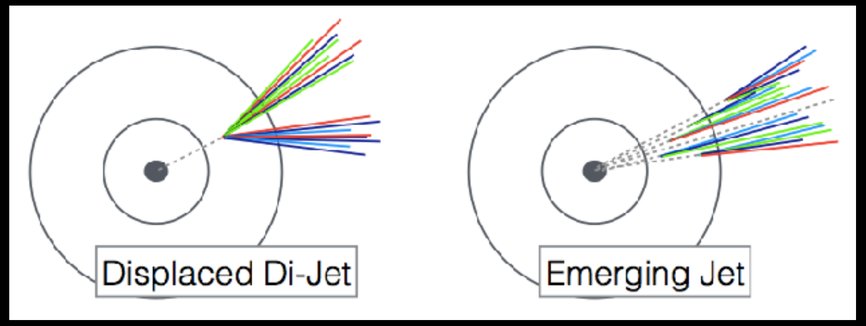

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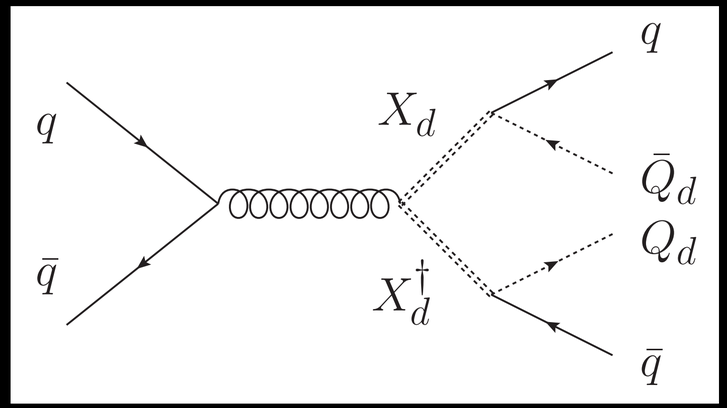

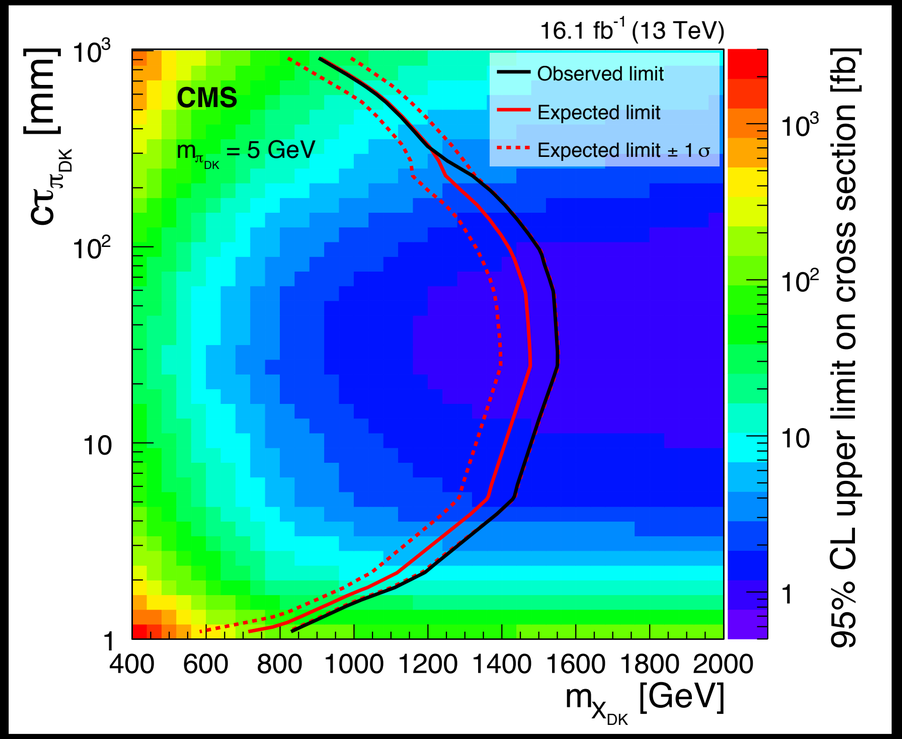

JHEP 02 (2019) 179