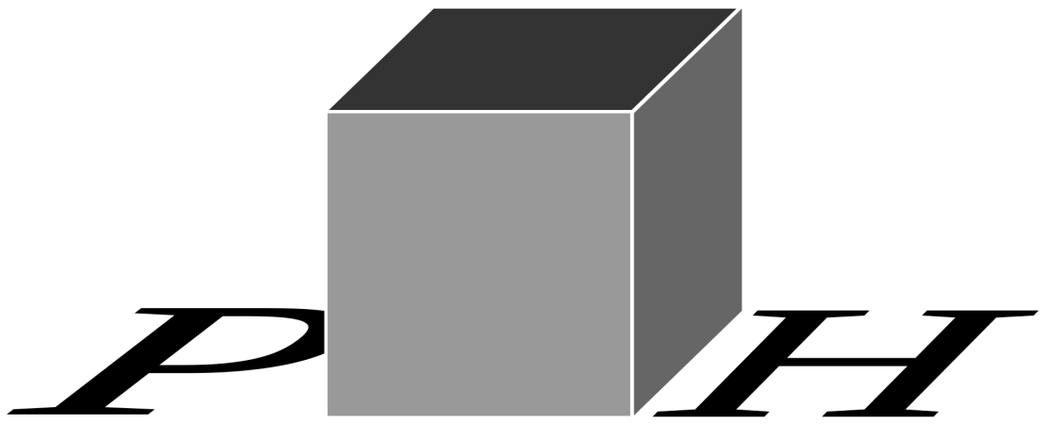
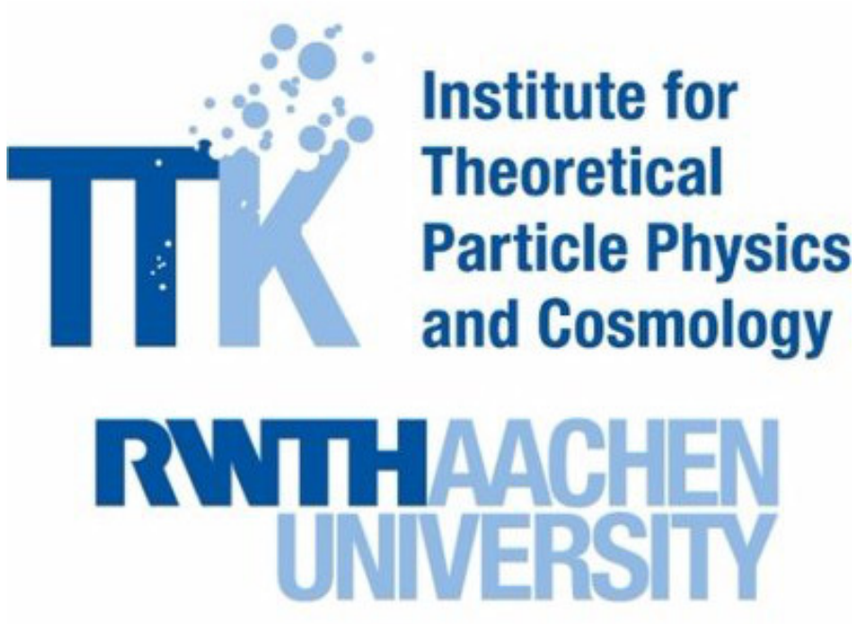
Theoretical overview of dark showers

Elias Bernreuther

LHCP 2021





Strongly interacting dark sectors

- Dark matter may be embedded in a rich **dark sector**.
- Huge wealth of models: How do we navigate the model space?
- Possible route: take inspiration from known SM interactions
- DM relic density as firm guiding principle

The dark sector may resemble QCD.

$$\mathscr{L} \supset -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a} + \overline{q_\mathrm{d}} i \not{D} q_\mathrm{d} - \overline{q_\mathrm{d}} M_q q_\mathrm{d}$$

- Dark quarks q_d in new non-abelian gauge group, e.g. $SU(N_\mathrm{d})$
- **Confinement** at some scale Λ_dark
- Exact spectrum unknown, can only be predicted on lattice

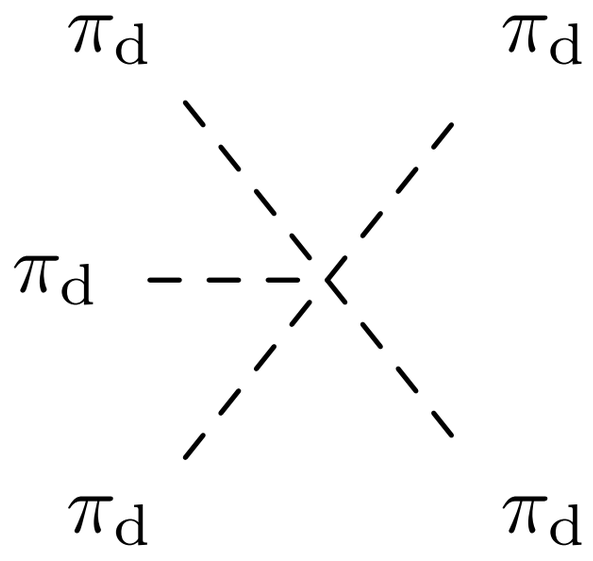
See e.g. Kribs & Neal, arXiv:1604.04627

Dark matter candidates

- $N_f^2 - 1$ **dark pions** π_d as massive Pseudo-Goldstone bosons

- If they carry a conserved charge, at least the lightest charged dark pions are stable.
  ➡ excellent DM candidates

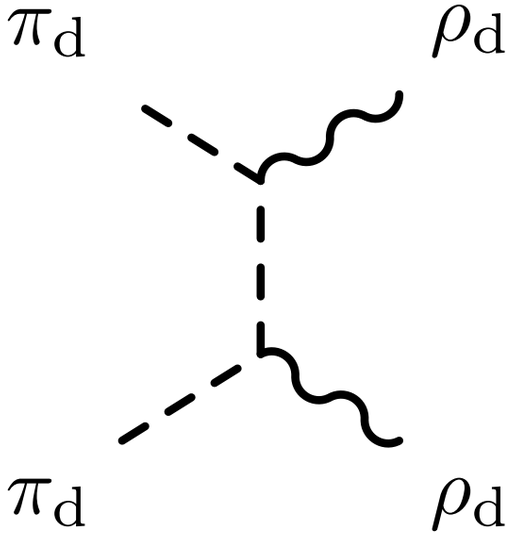
  DM relic density e.g. via SIMP mechanism
  ($3 \to 2$ annihilations) Hochberg et al., arXiv:1411.3727



- Heavier dark mesons are generically unstable, in particular ρ_d^0, which can mix with other vector bosons, e.g. Z' or dark photon.

  Different annihilation channels for dark pions,
  e.g. forbidden (semi-)annihilations

  Berlin et al., arXiv:1801.05805
  EB et al., arXiv:1907.04346



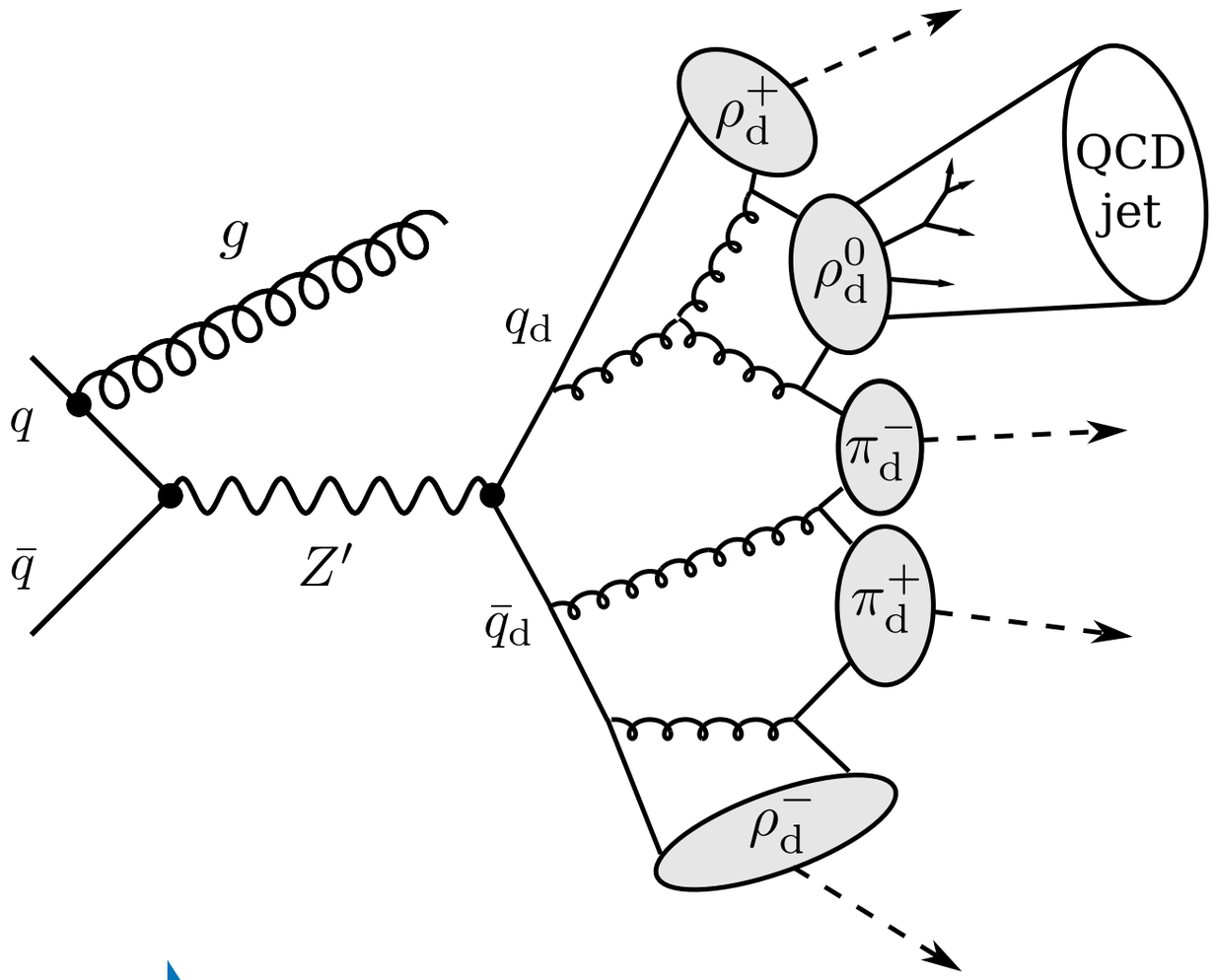
- Dark baryons typically stable

  Natural candidate for asymmetric DM
  (relic density set by particle-antiparticle symmetry)

Dark shower production

- LHC production of dark quarks leads to fragmentation and hadronisation in the hidden sector.
- Only publicly available MC tool at present: Pythia Hidden Valley module

Carloni et al., arXiv:1006.2911 & arXiv:1102.3795

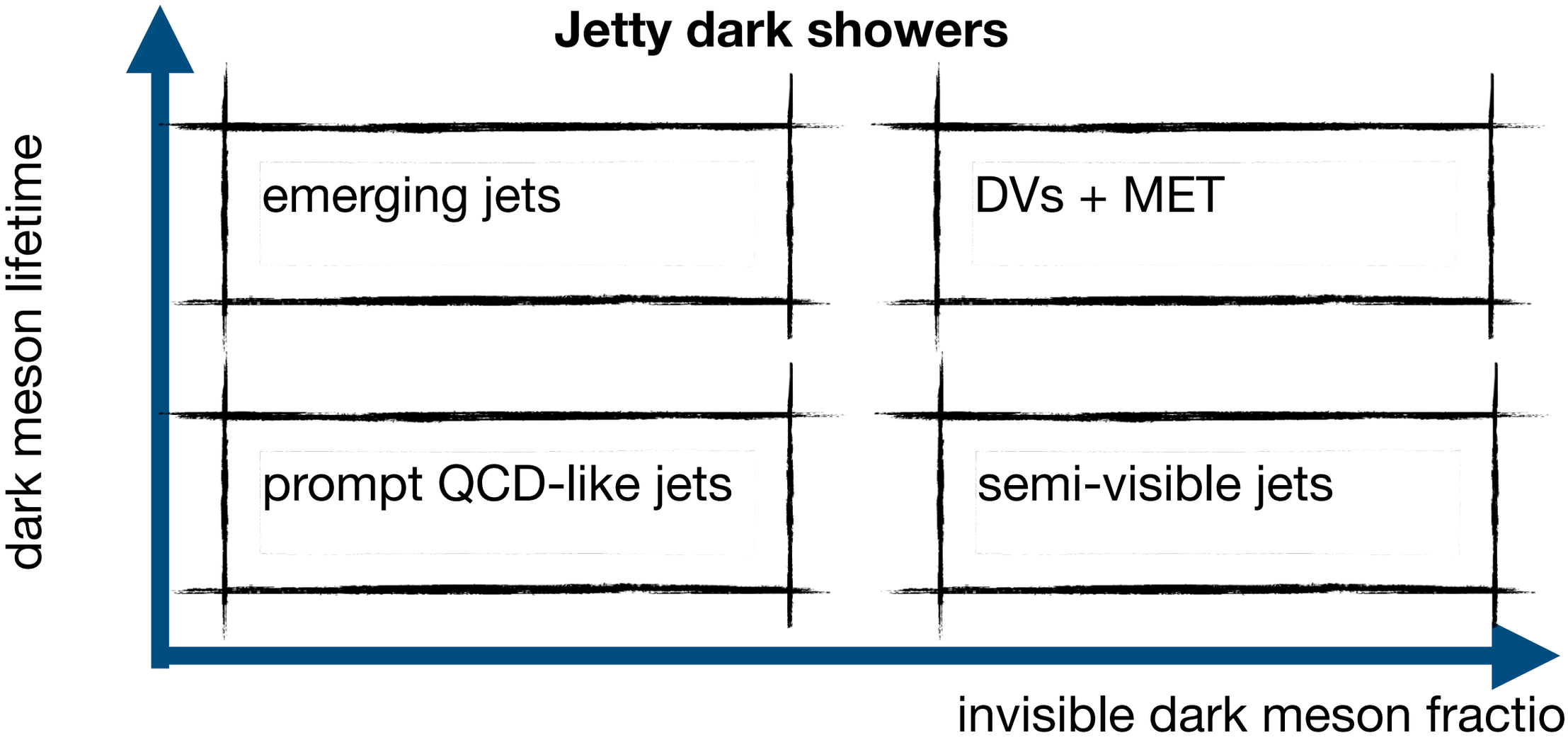


- Typically large multiplicity of dark mesons, varying from event to event
- Some dark meson species may decay visibly.
  Recent study of benchmarks:
  Knapen et al., arXiv:2103.01238
- Other dark meson species are stable.
- Signature depends on meson composition of shower.

Large model space, many uncertainties (e.g. hadronisation)

Motivates inclusive search programme

Signature space of dark showers



Non-jet signatures

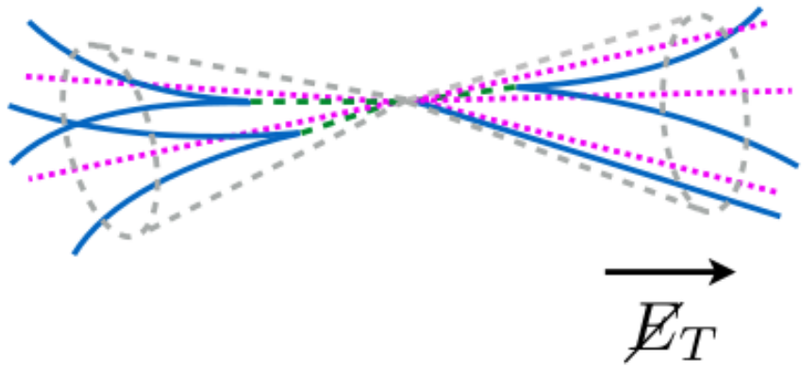
- Large ’t Hooft coupling $\lambda \gg 1$: ➡ wide-angle emissions ➡ SUEPs
  Knapen et al., arXiv:1612.00850
- The intermediate regime between jetty and spherical is challenging.
  see e.g. Cesarotti et al., arXiv:2009.08981

Semi-visible jets

- Mix of visible and invisible dark mesons leads to

  prompt jets + aligned missing energy

- Small $\Delta\phi = \min_j \Delta\phi(j, \not{E}_T)$

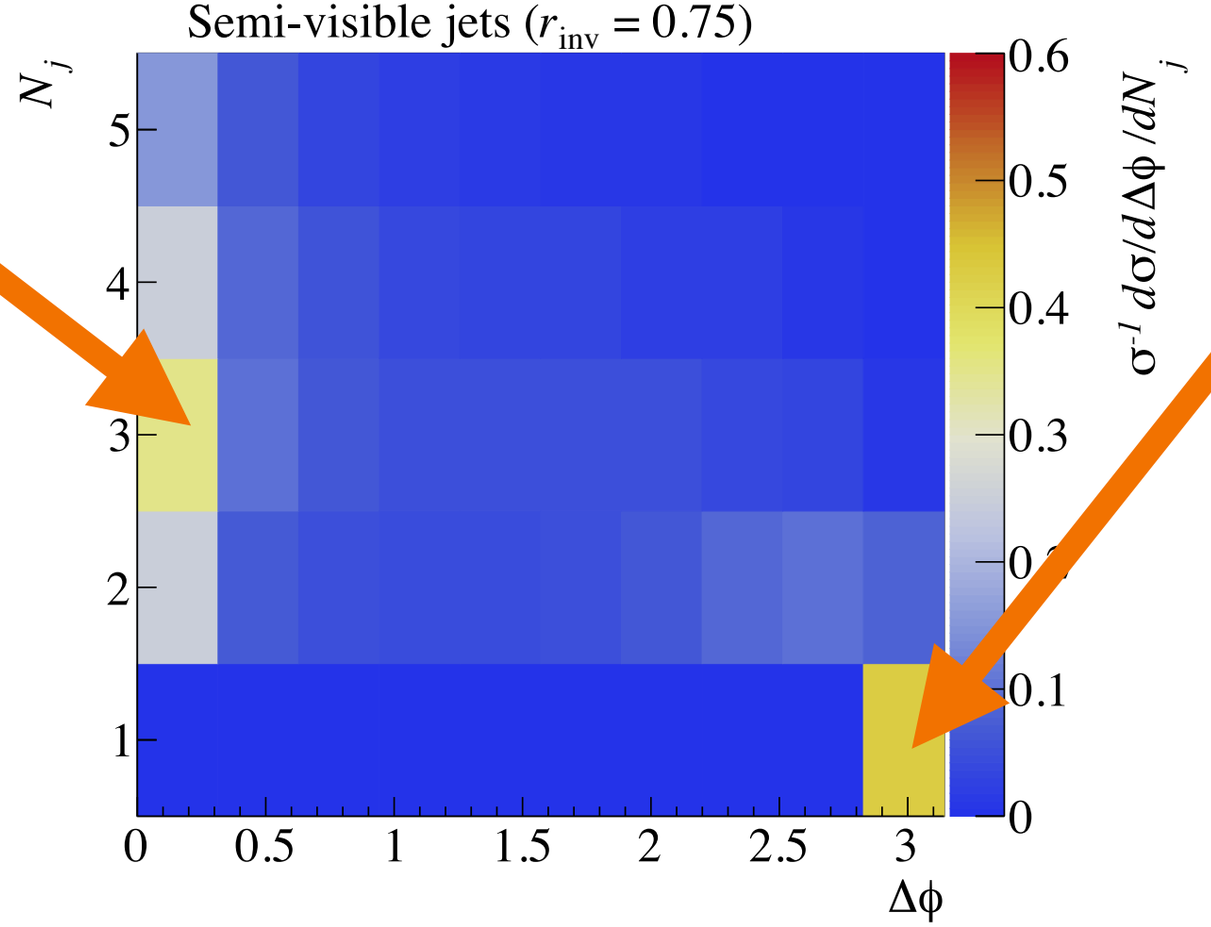


Cohen et al., arXiv:1707.05326

Both dark showers become partly visible,

missing energy aligned with a visible jet,

usually vetoed in standard searches to suppress large background from misreconstructed jets



One dark shower remains completely invisible,

monojet topology,

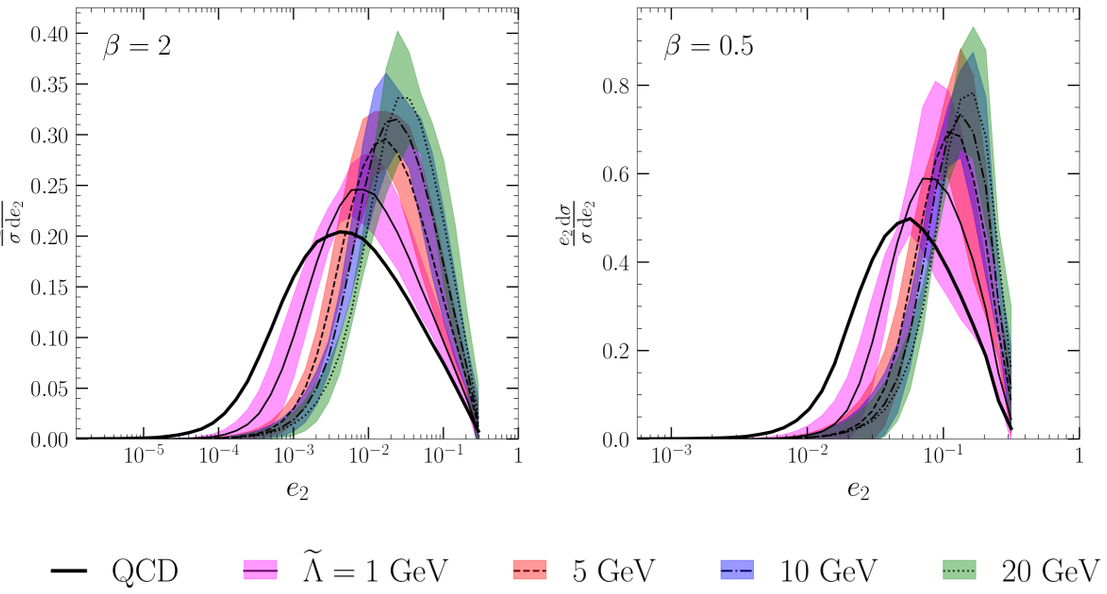
sensitivity from standard searches

Dark jet substructure

- Only handle on fully visible prompt dark jets, very useful also for semi-visible jets

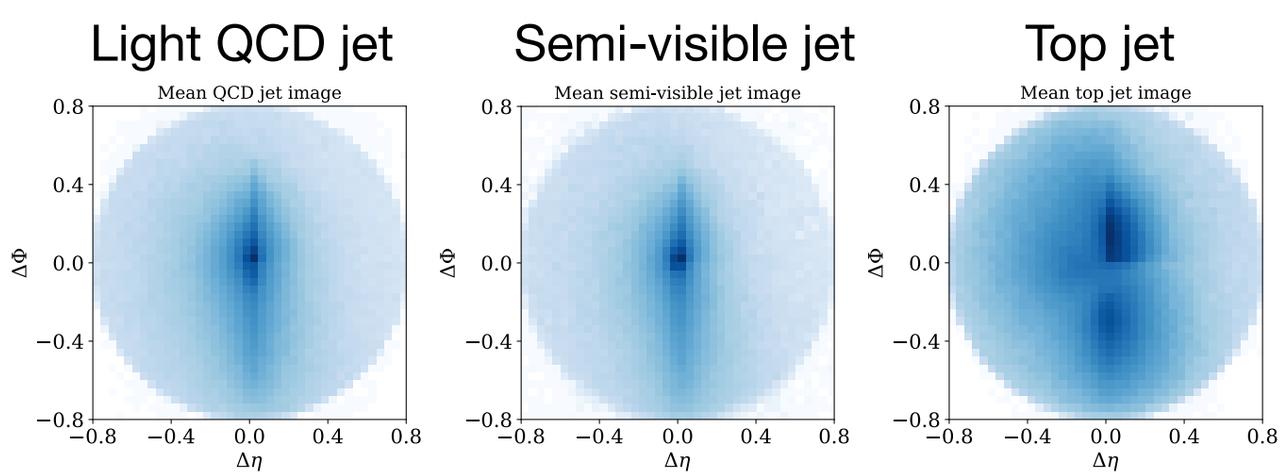
Kar, Sinha, arXiv:2007.11597

- **Jet substructure reflects non-QCD origin**, especially if Λ_{dark} is very different from Λ_{QCD}.



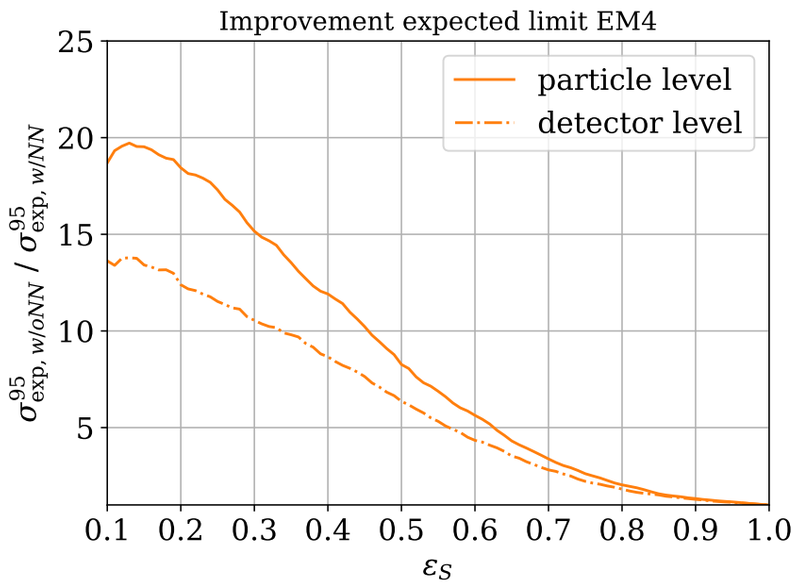
Cohen et al., arXiv:2004.00631

Tagging dark showers is hard:



EB et al., arXiv:2006.08639

- Large sensitivity improvement possible with deep learning (in particular **graph networks**)
- Very challenging for autoencoders
  → excellent benchmark for **anomaly detection**

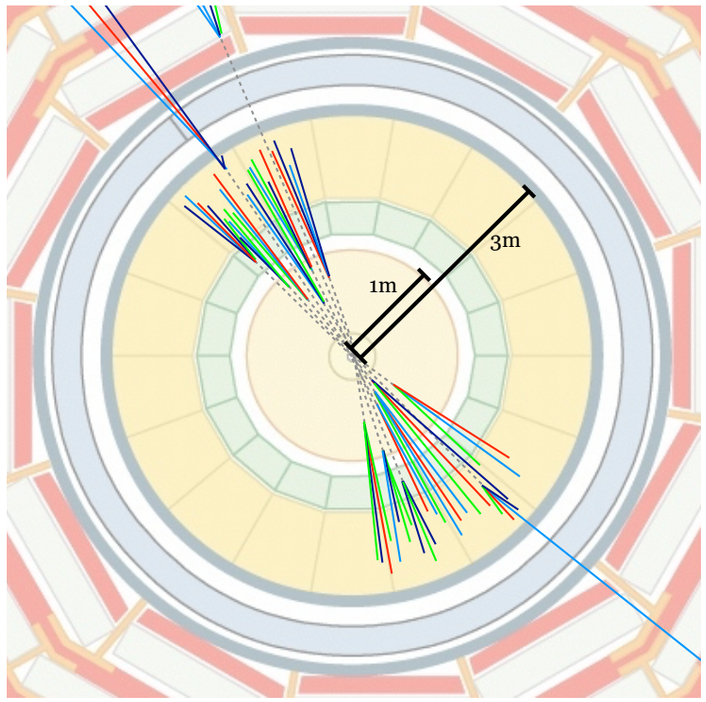


Signatures of long-lived dark mesons

Long-lived particles are a generic prediction of strongly interacting dark sectors.

If the shower is mostly visible:

- Jet composed of large number of long-lived dark mesons and little missing energy
  - → Emerging jets
- Typically not necessary to reconstruct individual DVs



Schwaller et al., arXiv:1502.05409

If the shower is mostly invisible:

- Small number of individual displaced vertices + missing energy
- Dark showers motivate search for GeV-scale DVs + MET.
- Existing searches are optimised for heavier DVs. EB et al., arXiv:2011.06604

Conclusions

- **Strongly interacting dark sectors** are well-motivated.

  Many ways to obtain DM relic abundance with **dark mesons or baryons**
- At the LHC strongly interacting darks sectors give rise to **dark showers**

  Large model space and theoretical uncertainties
- Can divide model space by **signatures**

  prompt dark jets, semi-visible jets, emerging jets, DV+MET, …

  Jet substructure and machine learning are very useful.

  Excellent benchmark for **anomaly detection**.
- Try to cover all signatures with **inclusive search programme**

Next up: Updates on these searches