CMS Perspective on Dark Showers

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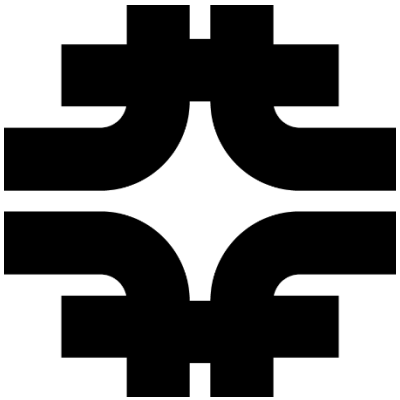
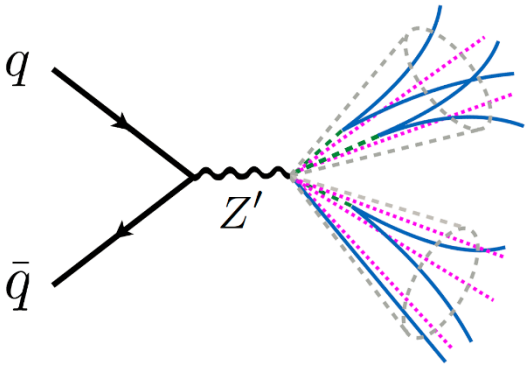
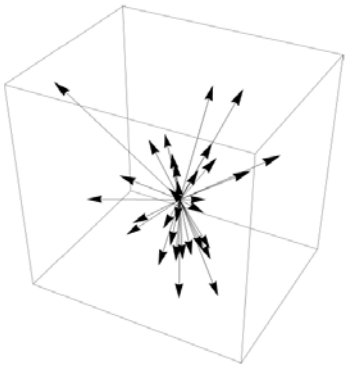
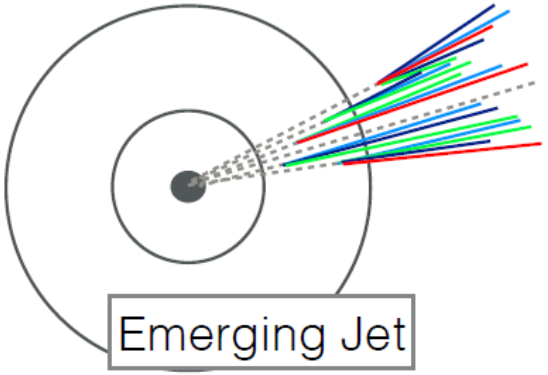


Phenomenology



Semi-visible jets





Soft unclustered energy patterns (SUEPs)

- CMS is exploring all of these signatures
  - Also different production modes, decay assumptions, etc.
- First collider search for dark showers: emerging jets (16.1 fb^{-1})
  EXO-18-001, JHEP 02 (2019) 179, arXiv:1810.10069

Event Generation

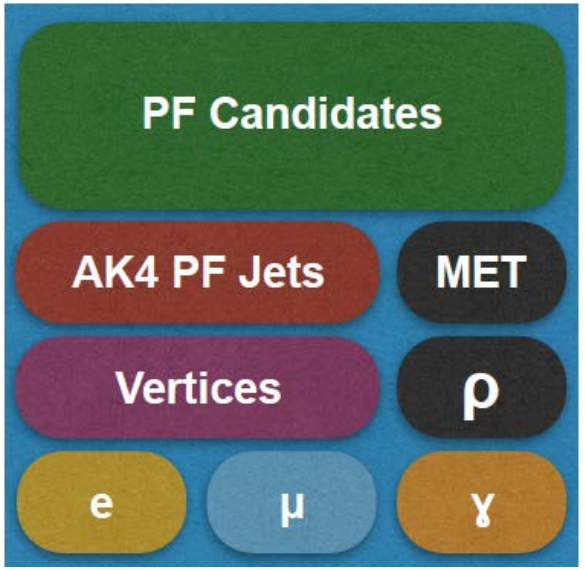
Several different methods:

- Generation & hadronization w/ Pythia8 Hidden Valley (HV) Module
  - Used for CMS searches so far
  - Employs (modified) copy of SM hadronization model
  - Leading order processes: Z' production, Φ pair production
- Generation w/ MadGraph, hadronization w/ Pythia8 Hidden Valley module
  - Being explored for new searches
    - ISR modeling more important in some cases
    - Some processes not available in Pythia8 (e.g. *t*-channel)
  - FeynRules models from: smsharma/SemivisibleJets
- Some parameters (lifetimes, branching fractions, etc.) often calculated "by hand" and passed to Pythia8

➢ "Wish lists" in backup: uncertainties are major item

Jet Triggers

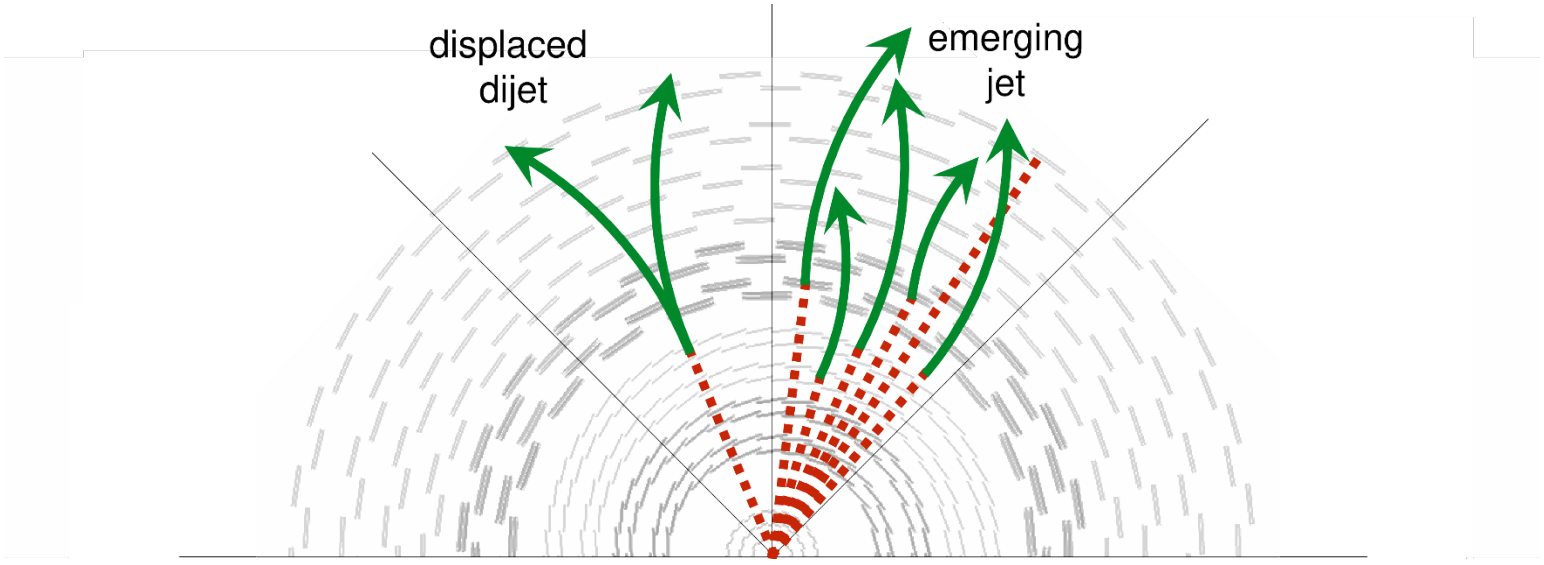
- CMS dark QCD searches currently trigger on jet p_T or $H_T = \sum p_T(\text{jet})$
  - Run 2 thresholds: jet $p_T \sim 500$ GeV, $H_T \sim 1000$ GeV
  - Can also use "substructure" triggers (e.g. $m_{trim} > 50$ GeV)
    - Slightly reduce p_T/H_T thresholds, improve efficiency
- Beginning to explore "scouting" data
  - Save just HLT Particle Flow objects
    - CMS HLT uses simplified reconstruction: fewer tracking iterations, etc.
  - Lower trigger thresholds: $H_T \sim 400$ GeV



arXiv:1808.00902

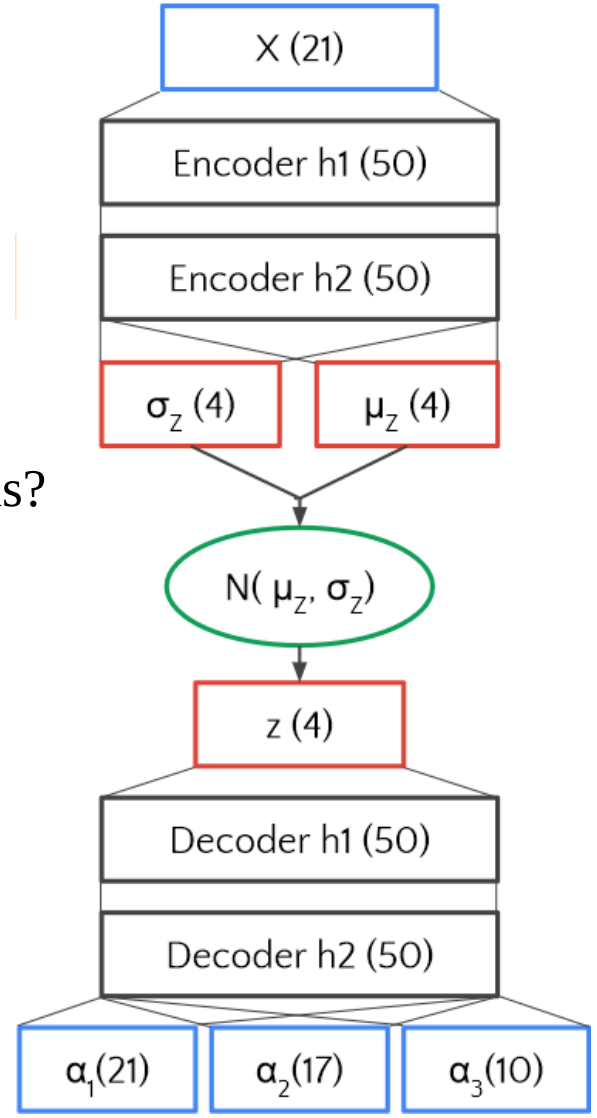
Other Triggers

- $\not{E}_T$ triggers: for cases with large fraction of invisible dark hadrons, or very long-lived dark hadrons (decay outside of detector)
  - CMS thresholds are high: typical offline cut $\geq$ 250 GeV
    - Exact offline cut depends on kinematic phase space
- Jet-$\not{E}_T$ triggers: offline $\not{E}_T$ threshold typically still high, small value added
- Displaced triggers: not clear yet if basic ones work well for emerging jets



Future Triggers

- L1 Track Trigger
  - Part of CMS Phase 2 upgrades
  - May enable new seeds for emerging jet trigger: displaced tracks, impact parameters
    - Track p_T threshold expected to be 2 GeV
      - Consider “L1 scouting” for lower thresholds?
- Anomaly detection (e.g. arXiv:1811.10276)
  - Use machine learning to find events that differ from expected processes
    - Need to understand how backgrounds can be reliably estimated
  - Deploy at L1 using hls4ml
  - Deploy at HLT using SONIC (inference as a service)



Simulation & Reconstruction

- Dark QCD models have many parameters
  - A single search may cover 100s, 1000s, or more specific signal models
- Full detector simulation is time consuming
  - Explore whether parametric fast simulation provides sufficient accuracy for signal samples
- Backgrounds often arise from reconstruction failures & instrumental sources
  - Tracking failures, hot/dead/weird cells, etc.
  - Delphes often does *not* model these correctly
    → pheno papers may underestimate backgrounds / overestimate sensitivity
- Custom algorithms and low-level information needed for optimal results
  - Can pose challenges for offline processing and disk usage of analysis data
  - Pursuing columnar analysis using Coffea for new searches
  - Phase 2: MIP Timing Detector will augment vertexing capabilities

Conclusion

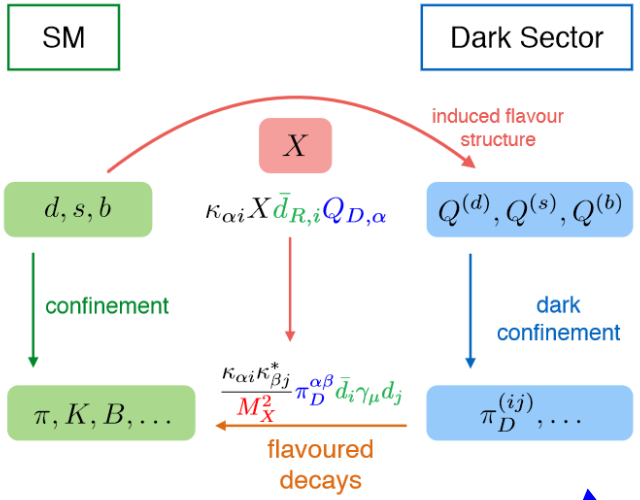
- CMS Dark QCD program is expanding
  - Investigating semi-visible jets, emerging jets, SUEPs
- Generators work sufficiently to provide signal samples to optimize and interpret analysis results
  - But many wish list items to improve capabilities
  - Generator uncertainties are a hot topic
- Currently, primarily jet-based trigger strategies are pursued
  - Other strategies ($\not{E}_T$, displaced, etc.) under consideration
  - Future prospects are good: L1 track trigger, anomaly detection
- Simulation and reconstruction also pose some (technical) challenges
- Look forward to more Run 2 results soon!
  - Later: Run 3 and Phase 2 datasets will improve statistical limitations

Backup

Generator Wish List

Pythia8:

- More processes (e.g. *t*-channel)
- Uncertainties as event weights
  - *Not viable* for searches to use different signal samples for each uncertainty variation
    → need event weights, even if less "accurate"
  - Pythia8 only provides SM parton shower weights
    - PDF weights can be recalculated on the fly
    - μ_R/μ_F weights *not* available
  - Would like to be able to vary HV parameters separately
- Hook to control flavor combinations for dark hadrons
  - Currently implemented as a hack (kpedro88:emg/230) for flavored emerging jet models (arXiv:1803.08080)
  - Add dark baryons? (HV module only has dark mesons)



Generator Wish List (cont.)

- Common tools to calculate dark hadron lifetimes and branching fractions → being considered as part of Snowmass efforts
- Comparison of SUEP hook (suep_generator) to Pythia8 “thermal” model
- Use of extra-dimension model for “intermediate” shower case (between jet-like and SUEP-like) (speculative, arXiv:2009.08981)

MadGraph:

- More standard support for common BSM processes (esp. *t*-channel)
  - Relevant for many DM searches, even beyond dark showers
  - FeynRules models can be tricky to use: decay width computation, reliability of phase space integration…
- Ability to add new *SU(N)* gauge groups
  - Improve modeling of HV radiation
  - Currently difficult (or even impossible?)