Dark QCD Model Building

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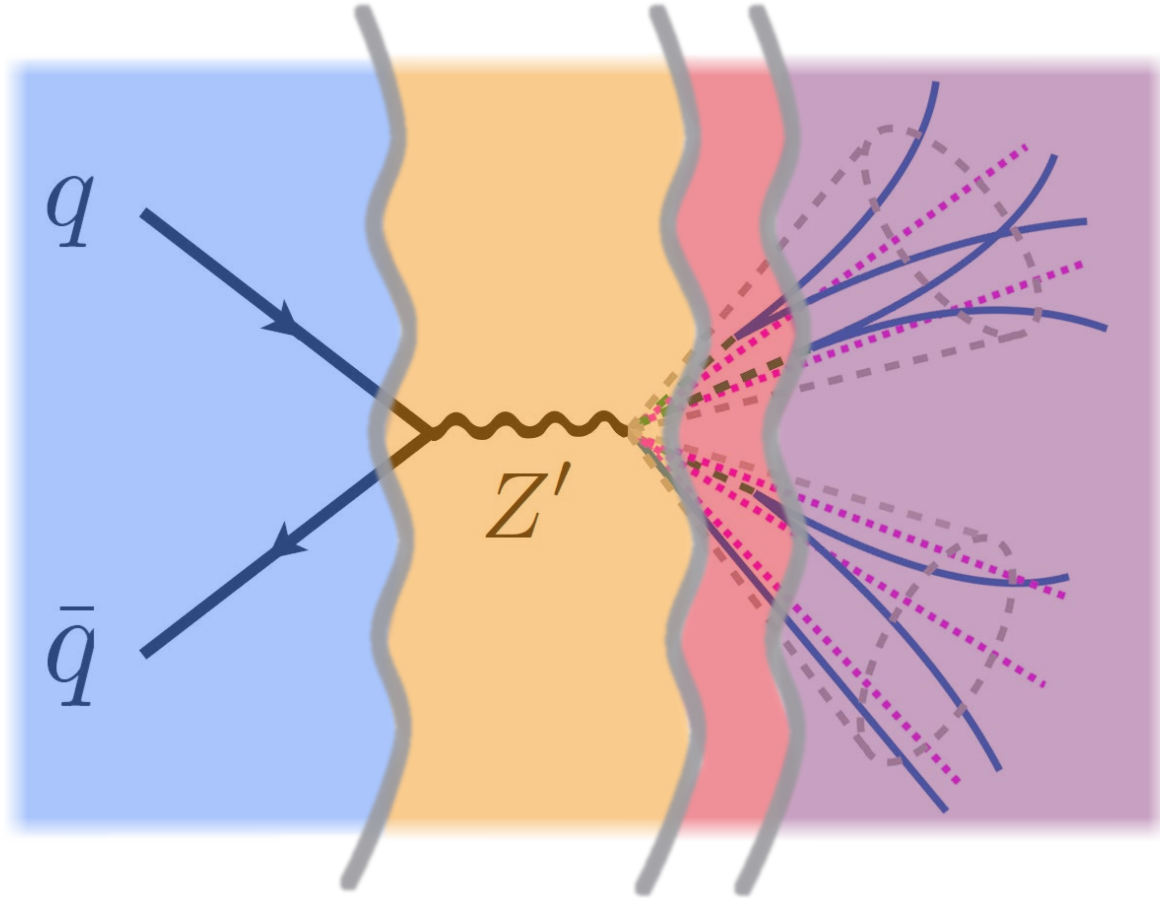
Goals

- Dark QCD models have many free parameters
  - Non-perturbative: relationships between UV and IR parameters must be determined through lattice calculations
- Try to map parameter values & combinations to *observables*
  - → reduce high-dimensional model parameter space to lower-dimensional space of *effective parameters*
  - Determine benchmark values/ranges of effective parameters that adequately represent, characterize, and span the original space
  - Need to understand any *degeneracies*
- Establish common benchmark models in order to compare results between different searches, experiments, etc.
- Build on and further develop Snowmass study

Anatomy of Dark Showers

Initial state
Parameters: PDFs

Dark sector
Parameters: N_c, N_f, Λ_{dark}, m_χ, h_{dark} spectrum (frequencies, mass scale, splittings, lifetimes)



Mediator
Parameters: mass, couplings

Final state
Parameters: decays (particle types, branching fractions)[3]

Mediators

- Z': couplings g_q, g_χ
  - LHC DM WG: $g_q = 0.25$, $g_{DM} = 1.0$
    $\rightarrow \Gamma_{Z'}/m_{Z'} = 5.6\%$, $BR(Z' \rightarrow DM) = 47\%$
  - $g_\chi = g_{DM}/\sqrt{(N_c N_f)}$ to maintain width and BR
- H: Yukawa couplings λ_{SM}, λ_χ
  - More production modes: VH, VBF, etc.
- Φ: Yukawa couplings $\lambda_{\alpha i}$ ($\alpha = \chi$ species, i = SM species)
  - Bifundamental, carries both dark and SM charges
  - Couplings may depend on chirality

➢ Focus on Z' case first (simplest)

Dark Sector

- $N_c > 2$ (avoid meson-baryon degeneracy, currently not simulated correctly)
  - Baryon production suppressed for higher N_c ($m_{baryon} \propto N_c$)
- $N_f < 3N_c$ for confinement
  - $N_f = 1$ also incorrectly simulated; start with $N_f = 2, 3, 4$?
- Λ_{dark}: define perturbatively via running gauge coupling α_{dark} or nonperturbatively via $m_\pi/\tilde{\Lambda}_{dark} \propto \sqrt{(m_\chi/\tilde{\Lambda}_{dark})}$
  - Assume $\Lambda_{dark} = \tilde{\Lambda}_{dark}$; implications?
  - Determine relationships from lattice results (also m_ρ vs. m_π)
    - Should lattice relationships always be assumed to hold?
  - $m_{Z'} \gtrsim 30\Lambda_{dark}$ for "jetty" behavior
- Dark hadrons:
  - Frequencies, e.g. prob(π) vs. prob(ρ); presence of any other species e.g. η
  - Mass splittings:
    - Degenerate quarks: only radiatively induced splittings (small)
    - Non-degenerate quarks: can allow $\pi_2 \to \pi_1$
    - $m_\rho < 2m_\pi$: potential three-body decays
  - Lifetimes τ_{dark}

Decays

- Dependent on mediator
  - Unless separate production and decay mediators
- Hadronic: decays to $q\bar{q}$
  - Democratic: equal BR for all q w/ $m_{h_{dark}} > 2m_q$
  - Mass insertion: prefer decay to heaviest available q
    - Need to account for mass running for correct BRs
    - Naturally enriches in heavy flavor
- Other possibilities: leptons, taus, photons, other flavor structures…
  - Also “cascade” decays: e.g. $h_{dark} \rightarrow \gamma_{dark}\gamma_{dark} \rightarrow \ldots$
- Try to treat as separately as possible from other model components
  - Independent variations easier for benchmarking

Generators

- Current vs. constituent dark quark mass: $m_{\chi_{const}} = m_\chi + \Lambda_{dark}$
  - What impact would other relationships have?
- Lund model parameters: aLund, bmqv2, rFactqv, sigmamqv
  - What ranges are reasonable?
  - What effects are visible?
  - Can uncertainties in these parameters be assessed as event weights?
    - Now they can! https://pythia.org/latest-manual/HadronizationVariations.html (for SM, to be copied to HV)
- Decay modes:
  - Can a dark shower be saved as an intermediate state, so decay mode can subsequently be varied independently, without inducing any additional statistical fluctuation?
- Empirical models:
  - Comparison of Pythia to Herwig (in development)

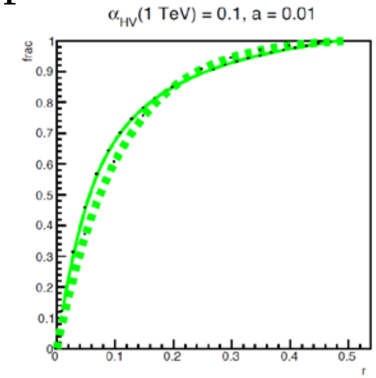
Observables

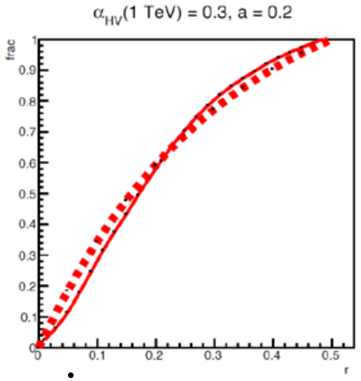
- Try to restrict parameter space to observables with significant, visible effects:

1. $m_{mediator}$
   - Couplings g_q, g_χ: pick benchmark values à la LHC DM WG
     - Variations can be assessed without new simulations for small $\Gamma_{Z'}/m_{Z'}$
2. m_{dark}: dark hadron mass scale
   - Cases: m_π vs. m_ρ, non-degenerate m_χ, $m_{dark} < 1$ GeV
3. Λ_{dark}: in combination with m_{dark}, determines m_χ
   - Can vary Λ_{dark}, m_{dark}, Λ_{dark}/m_{dark}, etc.
4. $r_{inv} = \langle n_{stable}/(n_{stable}+n_{unstable})\rangle \rightarrow$ *effective parameter*
   - Which UV parameter combinations can produce a given r_{inv} value?
     - Summary of existing models (few years old, should be updated)
     - If multiple combinations produce same r_{inv}, any observable differences?
     - How to compute for 3-body decays? $\langle p_T^{dark}/p_T\rangle$ not invariant w/ boost
5. τ_{dark}: dark hadron lifetime
6. Decay modes

More Effective Parameters

- First page may not fully encompass all effects of UV parameters & interactions between parameters
- Scheme proposed by Nishita Desai (then at TIFR): dark shower parameters
  - Average number of dark hadrons $n_{h_{dark}}$
  - Jet radius r_{max}
  - Jet shape parameter a → $f(r) = (1 - a^{r/r_{max}})/(1 - a)$





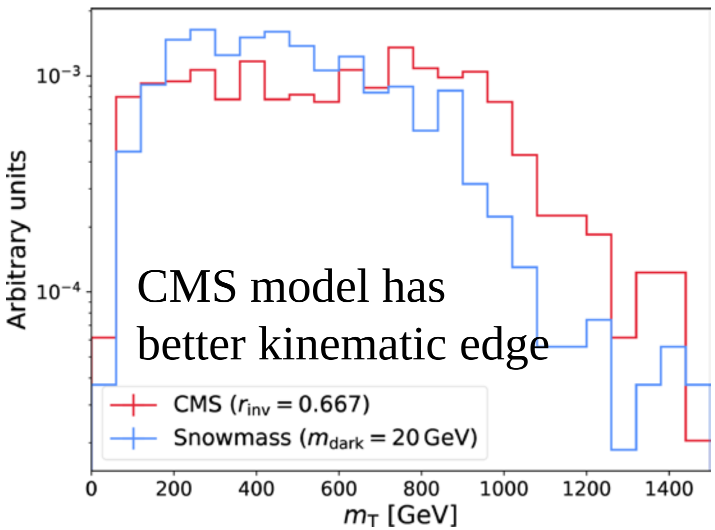
- Questions to answer:
  - How much do these parameters vary with UV parameters?
  - Is this scheme sufficient to capture jet substructure variations?
  - Can the number of parameters be reduced?
  - Would this scheme absorb/supersede some observables?
    - Λ_{dark}, m_{ρ}, non-degeneracies…
- Minimal space: ($m_{mediator}$, m_{dark}, r_{inv}, N jet parameters) → 4+ dimensions
  - How to scan effectively?
    - CMS does 2D scans of ($m_{mediator}$, x); tractable, but incomplete

Plan of Work

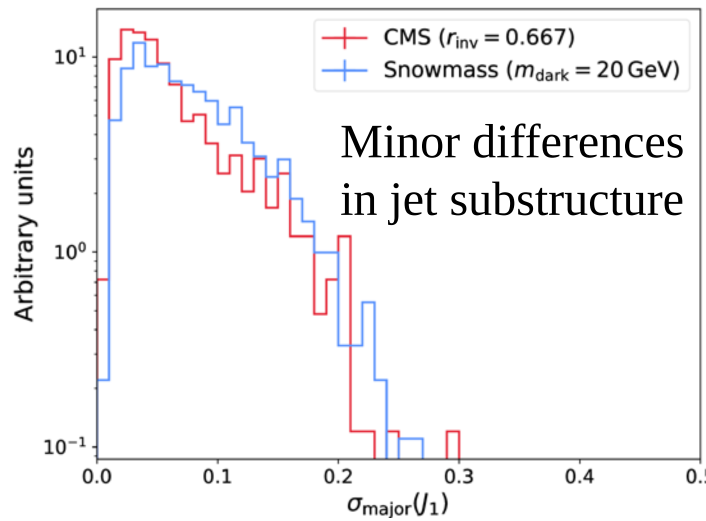
- Assess viable parameter ranges and assemble (mostly) complete models
  - Especially need to span r_{inv} from 0 to 1
- Compare event- and jet-level variables from simulation
- Derive minimal effective parameter scheme and ranges
  - Decide which parameters can be fixed:
    currently couplings, decay modes, potentially τ_{dark} (non-emerging case)
- cms-svj/model_building: repository for these studies
  - Generates consistent Pythia and Delphes cards given input configuration
    - Models added so far: CMS, Snowmass ($2m_\pi < m_\rho$)
    - Can also take external cards
    - Settings can be modified on command line; all final configurations automatically saved for reproducibility
  - Runs Pythia and Delphes
  - Creates histograms and makes comparison plots
    - Using scientific Python ecosystem
    - Can compute jet substructure
  - Users welcome!

Example Study

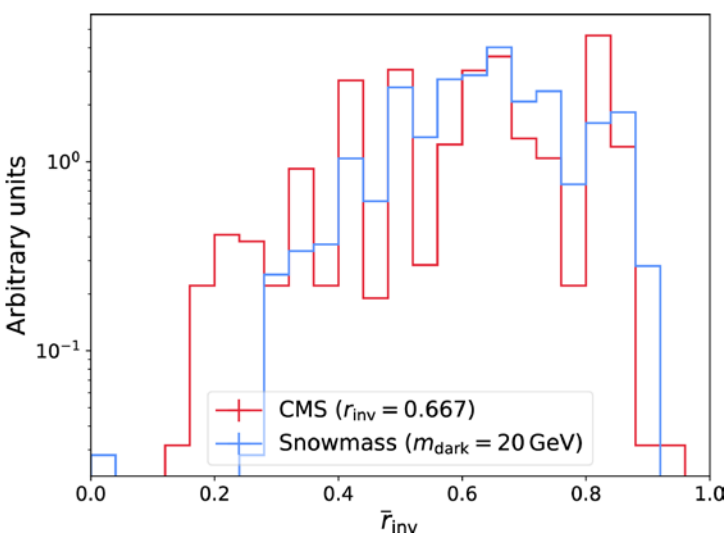
1. Snowmass benchmark model w/ $r_{inv} = 0.\overline{6}$, CMS-like scale (m_{dark} = 20 GeV)
2. CMS benchmark model w/ m_{dark} = 20 GeV, Snowmass-like $r_{inv} = 0.\overline{6}$



CMS model has better kinematic edge



Minor differences in jet substructure



Compute per-event r_{inv} to compare w/ specified value

CMS: $\langle \bar{r}_{inv} \rangle = 0.63$

Snowmass: $\langle \bar{r}_{inv} \rangle = 0.65$