Darkshowers – snowmass whitepaper

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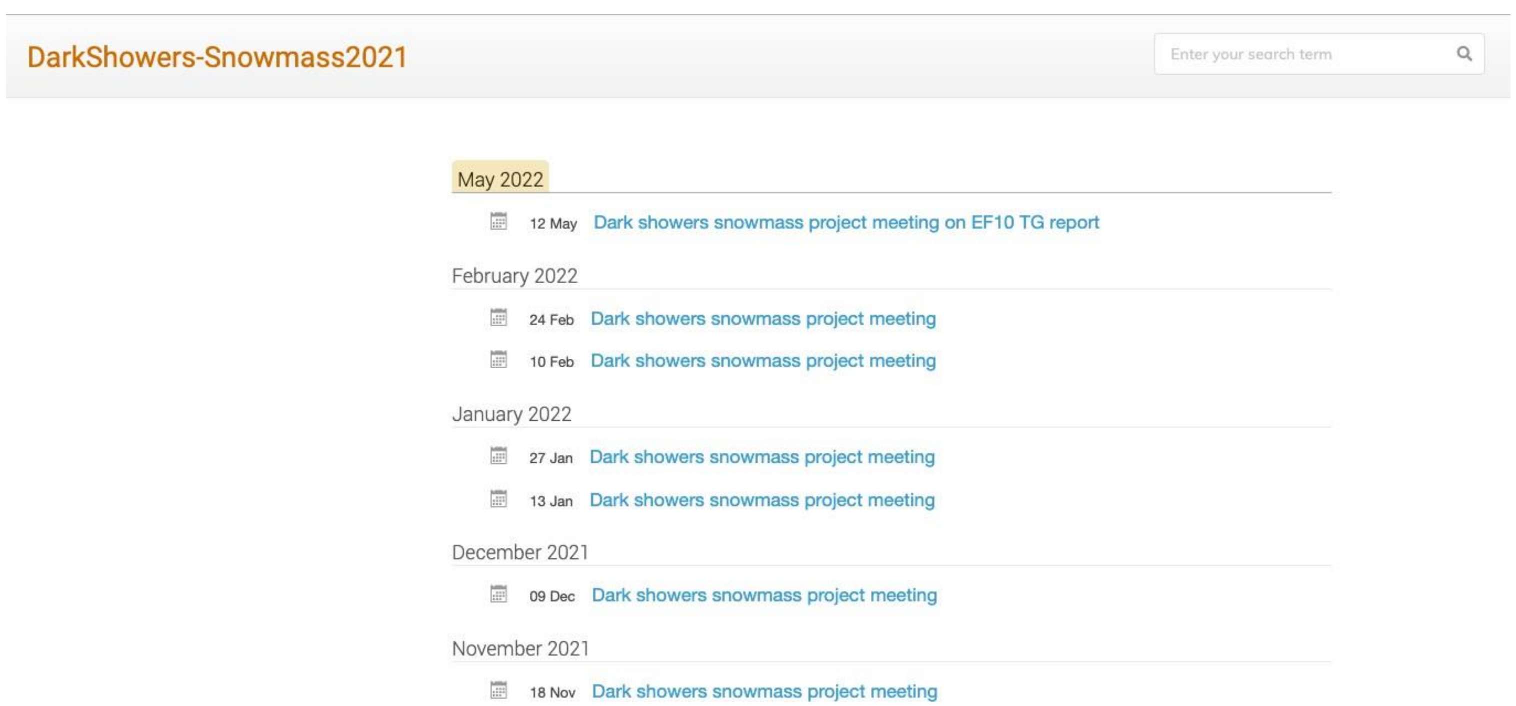
On behalf of snowmass dark showers group
Based on arXiv:2203.09503

Presented and lightly edited by Matt Strassler (Harvard)
DMWG Jan 12, 2023

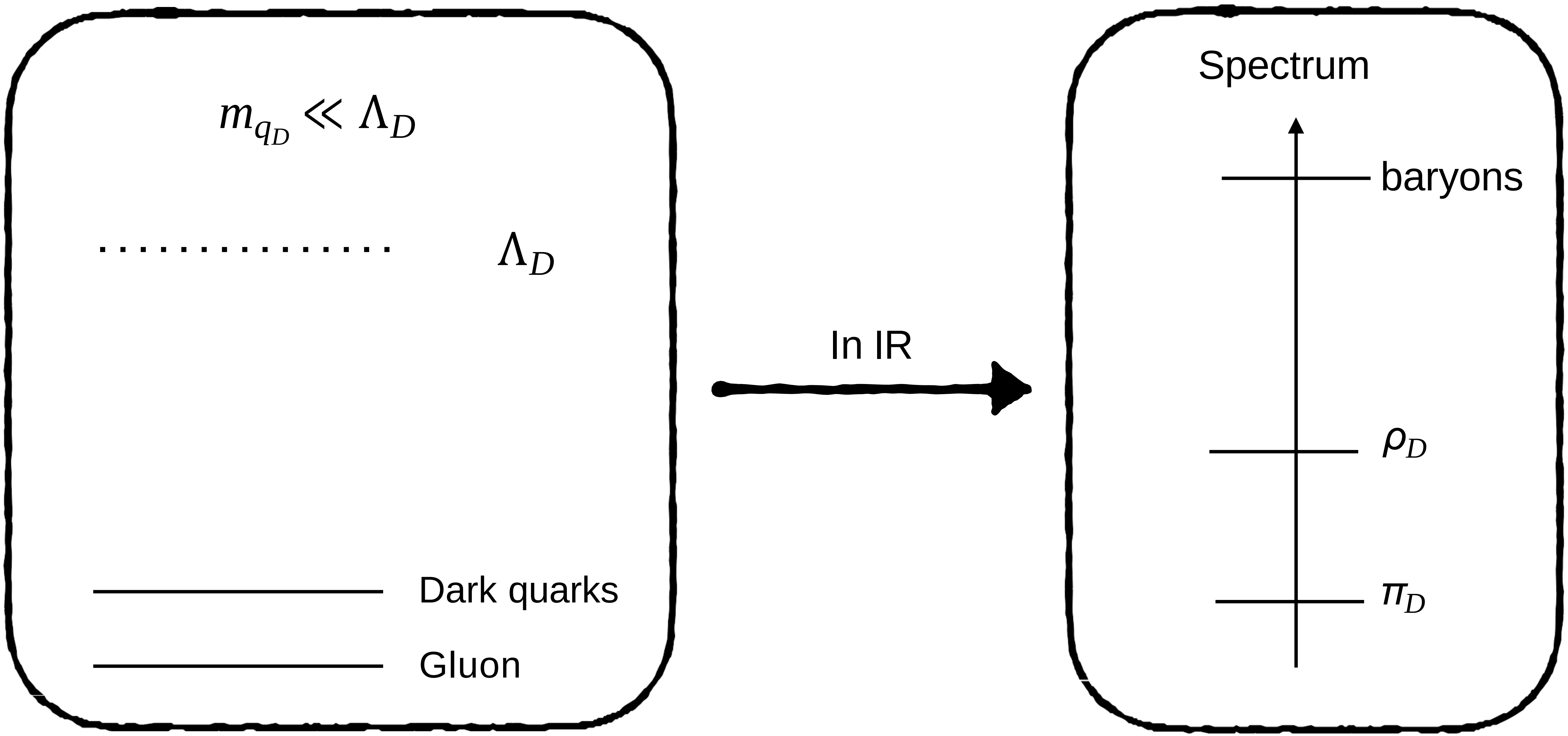
Snowmass darkshowers

- The snowmass darkshowers group was formed during the snowmass process and began of course with formation of a creative logo
- Met at least once a month to discuss ongoing work
- A total of ~70 members on the mailing list, demonstrates critical mass
- Group consists of theorists (incl. PYTHIA8 authors) and experimentalists, enabled cross talk and cohesive progress; fully bottom up approach
- All meetings slides, recording and live minutes can be found at this link
- Mailing list remains active: dark-showers-snowmass21@cern.ch



The Basic Scenario

Confining Hidden Valley / Dark Sector



- If this is the reality of nature, how do we look for it?

A Class of Non-Abelian Theories

- Restricted our thinking about new SU(N) gauge group uncharged under the SM
- HV/DS Parameters: # dark colors, # dark flavors, confinement scale, quark masses;
- Mediator Parameters: mass, couplings to SM and HV/DS
- Calculate (lattice and direct estimates): dark hadron masses, decay modes, lifetimes
- Simulate (PYTHIA8): dark hadron production

Different regimes in signature space

This is a continuum!

Theories that make
(dark) jets (QCD-like)
$\alpha_D N_{c_D}$ small

Theories that instead make
Soft Unclustered Energy Patterns (SUEPs)
$\alpha_D N_{c_D}$ large

This refers to the coupling constant
evaluated in the showering regime

Theories with dark jets

Mainly two mediators considered so far: s-channel Z' and t-channel bifundamental ϕ

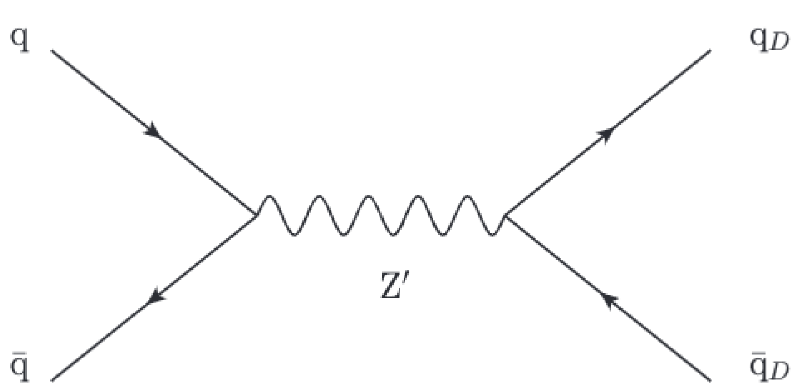
Strassler & Zurek '06
Carloni & Sjostrand '10

- Signature space with complex jets, semivisible jets, emerging jets, trackless jets
- Treat dark rho and dark pions on same footing
- Simulation based on older Pythia Hidden Valley module

See also:
Beauchenese, Bertuzzo, Di Cortana arXiv:1712.07160
Bernreuther, Kahlhoefer, Krämer, Tunney arXiv:1907.04346
Knapen, Shelton, Xu arXiv:2103.01238

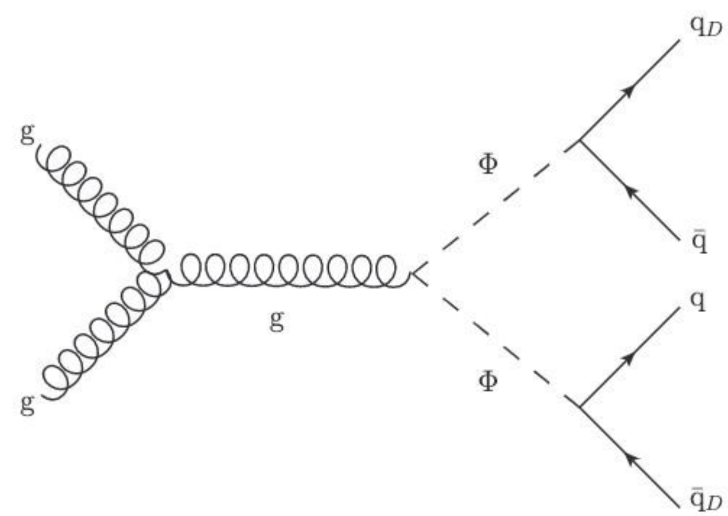
s-channel (Z') production

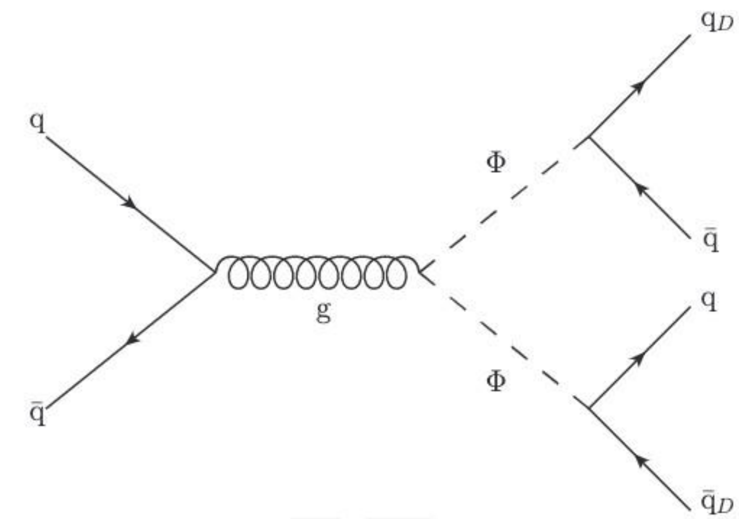
$$\mathcal{L} \supset Z'_\mu \left(g_q \bar{q}_i \gamma^\mu q_i + g_{q_D} \bar{q}_D^\alpha \gamma^\mu q_D^\alpha \right)$$



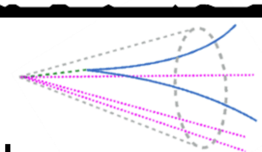
t-channel (bifundamental) production

$$\mathcal{L} \supset -\kappa_{\alpha i}\, q_D^\alpha \phi\, \bar{q}_{Ri} + h.c.$$

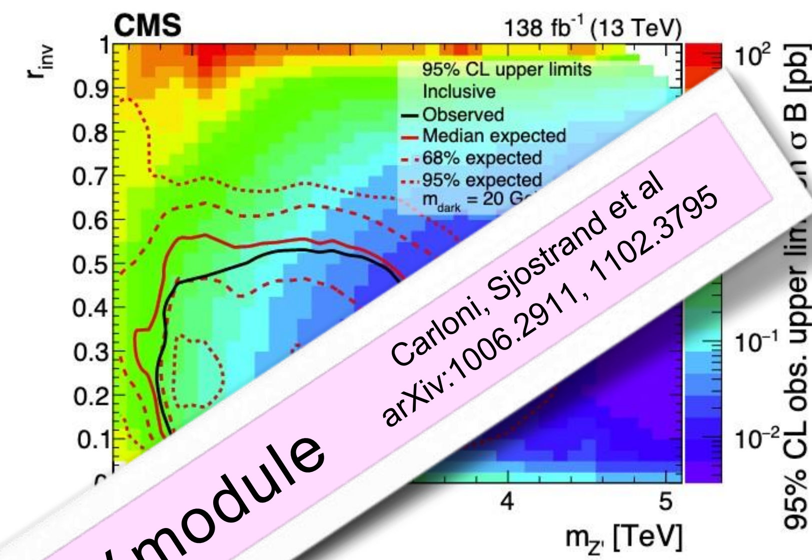




Semivisible jets



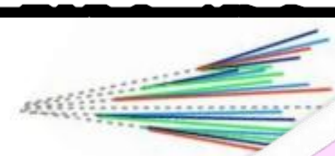
- Unstable dark mesons decay promptly via two body decays
- $r_{inv} = N_{stable}/(N_{stable} + N_{unstable})$ Cohen, Lisanti, Lou arXiv:1503.00009
- Small ${}_{inv}$: dijet search strategy; Large ${}_{inv}$: monojet searches; Intermediate ${}_{inv}$: Dedicated searches



CMS collaboration arXiv:2112.11125

…imental for semivisible jets

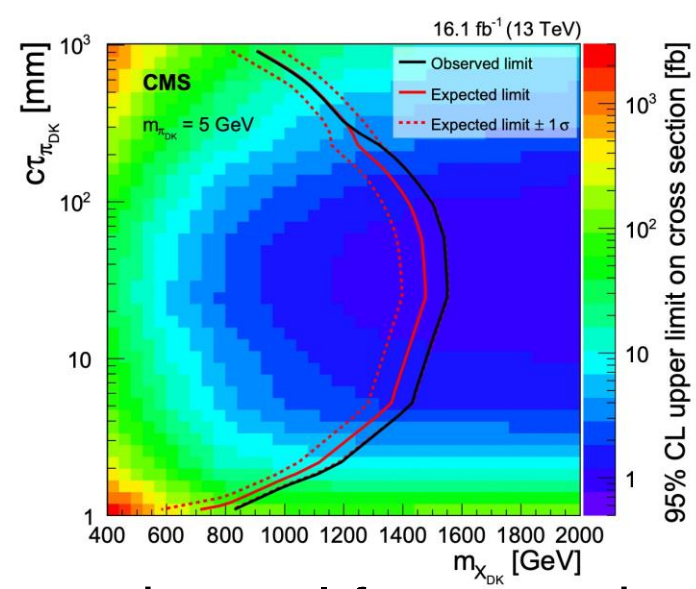
Emerging jets



- Dark mesons with finite lifeti… multiple displaced vertic…
- Unflavoured case: …e for all dark hadrons Schwaller, Stolarski & Weiler arXiv:1502.05409
- Flavoured case: diagonal, off-diagonal dark hadrons have different lifetime

All olser studies use PYTHIA8 (<8.307) HV module

Carloni, Sjostrand et al arXiv:1006.2911, 1102.3795

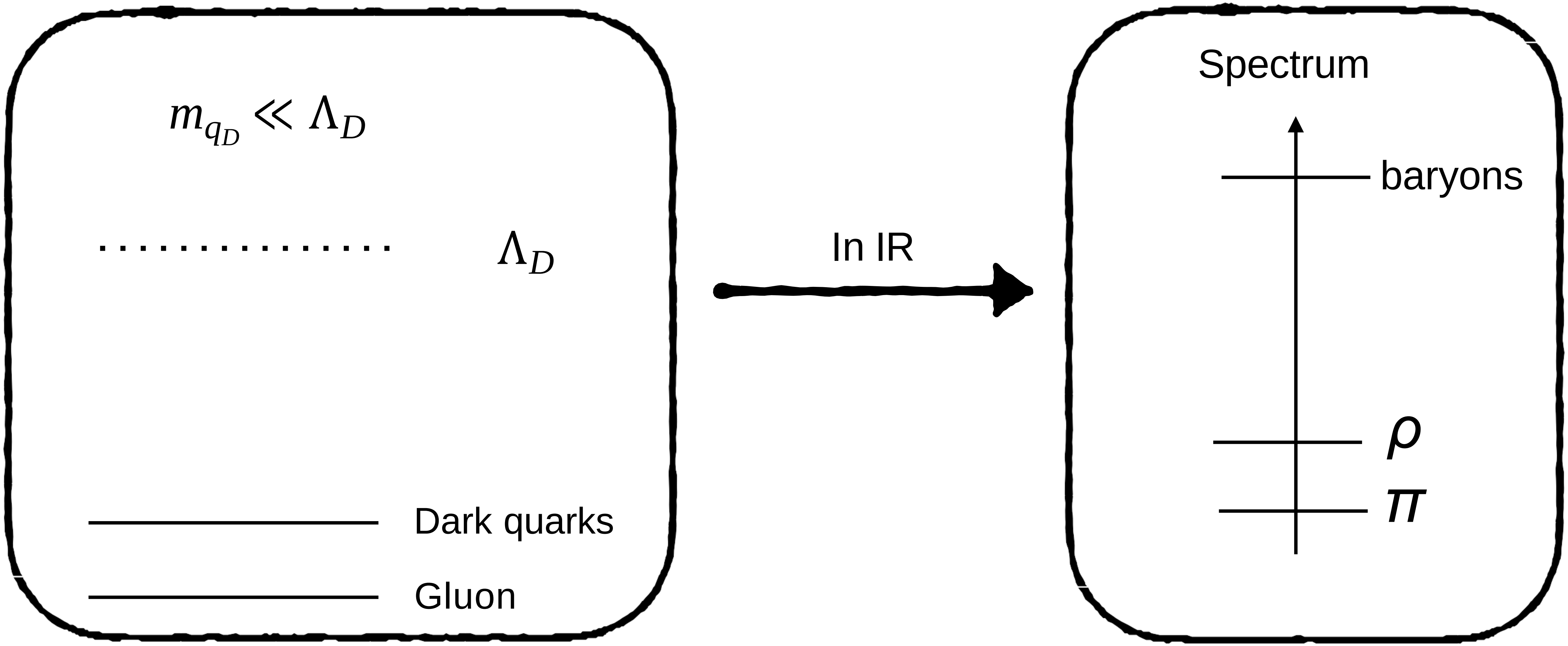


CMS collaboration arXiv:1810.10069

First experimental for emerging jets

Phenomenology has not always been realistic e.g. missing particles and symmetry constraints; now updated within snowmass study

Strongly interacting theories: composition



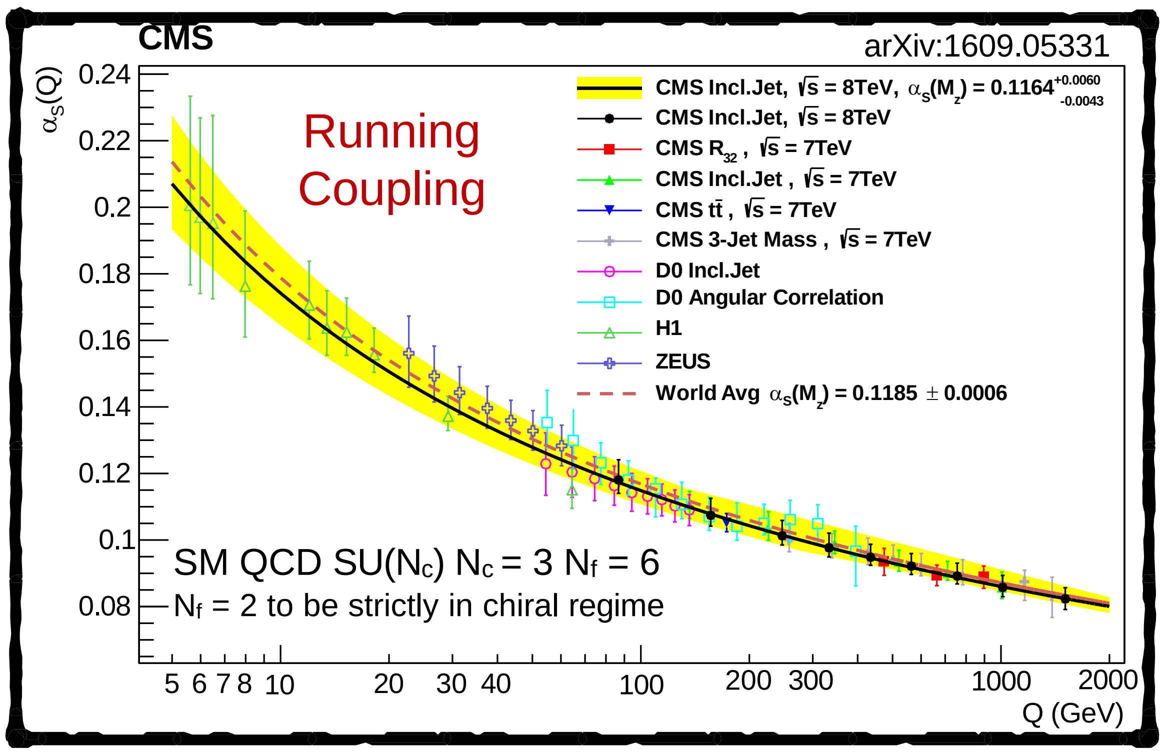
UV physics contains

- Gauge fields (gluons)
- Matter fields i.e. Dirac/Majorana fermions, Scalars (in representation N_r)
- Here: mainly **mass degenerate** Dirac fermions in fundamental rep

- Two discrete parameters N_{c_D}, N_{f_D}
- Two continuous params m_{q_D}, $\alpha_D(\mu)$ (UV)
  - $\Lambda_D, m_{\pi_D}/\Lambda_D$ (IR)
- N_{c_D} = 2 and/or N_{f_D} = 1 special cases

QCD-like theories

- For mass degenerate fermions, theory has four free parameters N_{c_D}, N_{f_D}, m_{π_D}/Λ_D, Λ_D



Confining Regime

Nc	Nf
3	<< 9
4	<< 13
5	<< 16
6	<< 18

arXiv:2008.12223

Dividing line between confining and conformal not precisely known yet

$$\alpha_D(Q^2) = \frac{1}{\frac{11 N_{c_D} - 2 N_{f_D}}{6\pi} \log\left(\frac{Q}{\Lambda_D}\right)}$$

plus higher loop corrections

- QCD-like theories: asymptotically free theories in chirally broken phase
- $N_{c_D} = 2$ is pseudo-real group and hence different,

  care should be taken (applicable even for new PYTHIA8(8.307) HV module)!

  - For these theories, pions ($q\bar{q}$) are mass degenerate with baryons (qq)
  - Two flavour theory has five ‘pions’, PYTHIA8 HV will simulate only three = $(N_{f_D}^2 - 1)$
- Always use $N_{f_D} > 1$; $N_{f_D} = 1$ theory has no broken symmetry → no pions!

See also talk by M. Strassler at LLPX

Mass spectrum

- $SU(Nc_D), Nc_D > 2$ theory with N_{f_D} mass-degenerate quarks has $N_{f_D}^2 - 1$ mass-degenerate dark rho, pions, plus spin-0 and spin-1 singlets

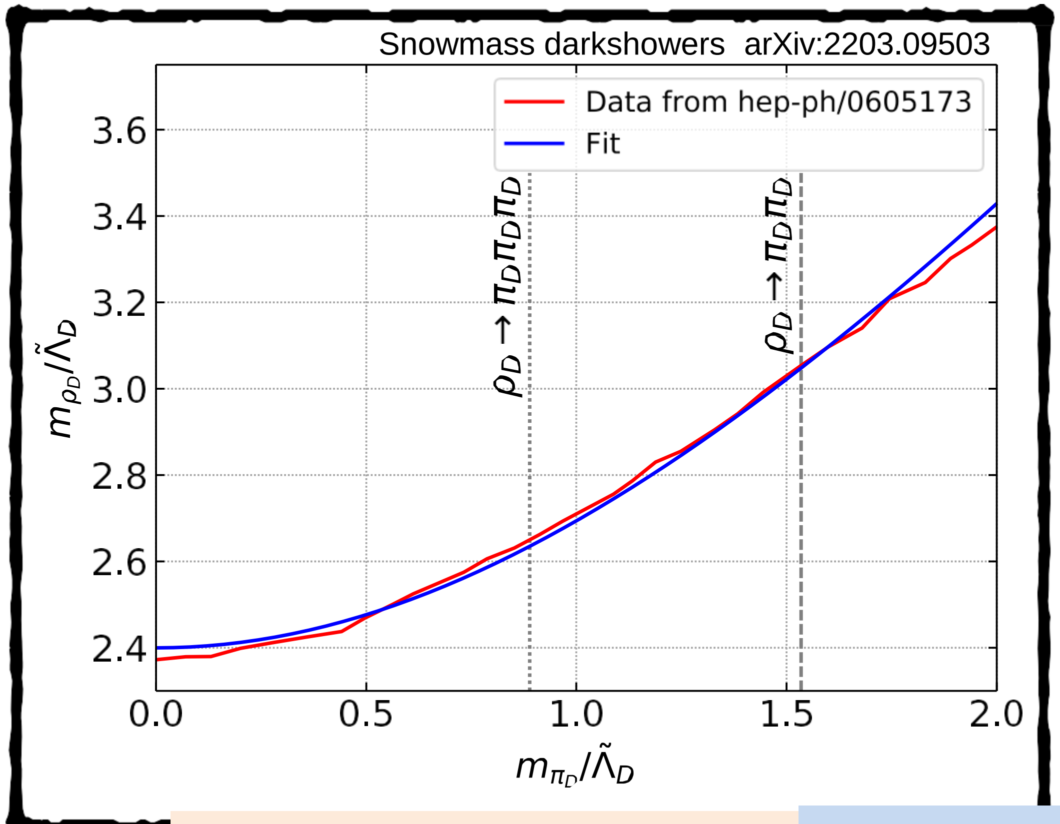
$N_f = 3$

$$\pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K^0} & -\sqrt{\frac{2}{3}}\eta \end{pmatrix} + \eta' \qquad \rho_\mu = \begin{pmatrix} \frac{\rho^0_\mu}{\sqrt{2}} + \frac{\omega_\mu}{\sqrt{6}} & \rho^+_\mu & K^{*+}_\mu \\ \rho^-_\mu & -\frac{\rho^0_\mu}{\sqrt{2}} + \frac{\omega_\mu}{\sqrt{6}} & K^{*0}_\mu \\ K^{*-}_\mu & \overline{K^{*0}_\mu} & -\sqrt{\frac{2}{3}}\omega_\mu \end{pmatrix} + \phi$$

- Lattice data used to derive (N_{c_D}, N_{f_D} independent) fits

$$\frac{m_{\pi_D}}{\tilde{\Lambda}_D} = 5.5\sqrt{\frac{m_{q_D}}{\tilde{\Lambda}_D}} \qquad \frac{m_{\rho_D}}{\tilde{\Lambda}_D} = \sqrt{5.76 + 1.5\frac{m^2_{\pi_D}}{\tilde{\Lambda}^2_D}}$$

NOTICE: EITHER pion is significantly lighter than rho OR glueballs are stable and need to be included among hadrons



REGIME 1 | REGIME 2

Danger: Over-Simplification in Experimental Searches

Here all subscript "D"s are dropped for brevity

1) Assumption that dark quarks are all degenerate

This eliminates cascade decays like those that are common in QCD

e.g. $\eta \to \pi\pi + SM$, $K \to \pi + SM$

Physically possible, but very uncommon in models:

- requires a symmetry to create degeneracy,
- but must badly break the same symmetry to allow decays to SM!

Does This Matter?

2) Assumption that dark hadrons are degenerate (typically $m_\pi = m_\rho$)

This eliminates

e.g. $\rho \to \pi\pi$, $\rho \to \pi + SM$

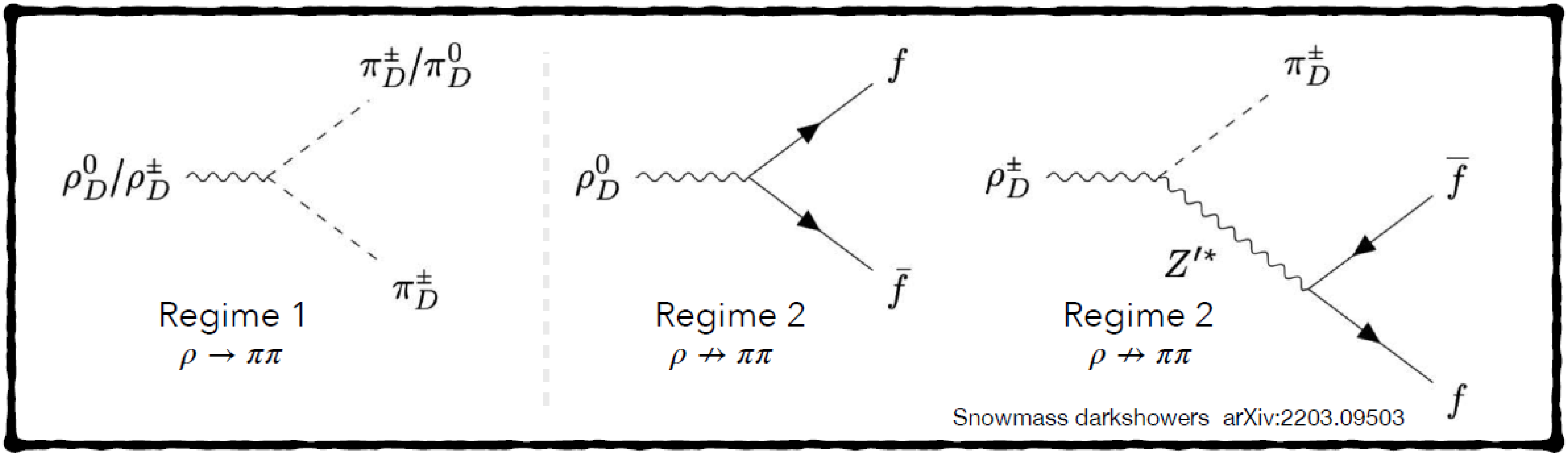
UNPHYSICAL! This never happens unless quarks are heavy, which implies

- $m_\pi \gg \Lambda$, in which case
- Dark glueballs are stable and the whole dark hadron analysis has to be redone
- (and PYTHIA8 can't do hadronization)

This Does Matter!

Dark mesons decays

- Analysis of broken symmetries and chiral Lagrangian set dark meson decays



- Regime 1, $m_{\rho_D} > 2m_{\pi_D}$: ρ_D decays to π_D
- Regime 2, $m_{\rho_D} < 2m_{\pi_D}$: ρ_D decays to SM via mixing with Z' or via three body decays (can lead to LLP!)

See also Berlln, Blinov, Gori, Schuster, Toro arXiv:1801.05805

  - Not captured in previous LHC phenomenology
  - PYTHIA8 has had no possibility do set different decay modes/lifetimes for specific ρ_D
- In either regimes, π_D can also decay if π_D and Z' get mass from same dark Higgs i.e. pion mixes with longitudinal mode of Z'
- If no mixing between π_D and Z': can stabilise the π_D at least at collider scale

HV/DS Hadron Decays to the SM

Decay modes and lifetimes

- Depend on kinematics, spin, and couplings of hadron and mediator
- Must be calculated by the theorist for each model

Common threads:

- Spin-1 hadrons easily give dilepton resonances
- Spin-0 hadrons easily give heavy flavor resonances (b's, c's, tau's, mu's)
- Spin-0, -2 can give gluon pairs, photon pairs
- Cascade decays can give non-resonant dileptons
- LLPs can appear at any stage (including in cascade decays)
- MET with any stable, metastable HV/DS particles

Considerable complexity is possible!

- Need to target simple signatures, but
- Need to ensure that search strategies don't exclude complex signatures

Example: Z' mediator decay to dark quarks (or H' mediator to dark gluons)

- Showering ensues
  - May be standard, PYTHIA-like shower if asymptotically free or conformal with $\alpha_D N_c \ll 1$
    - Jets of dark hadrons form ; breadth, shape determined by $\alpha_D(\mu)\, N_c$
  - May be a non-standard shower if asymptotically conformal AND $\alpha_D N_c \gg 1$
    - Gluons, and eventually hadrons, will be more broadly distributed

- Hadronization follows
  - Might be QCD-like theory in which hadronization is like QCD
  - Might be somewhat QCD-like in which hadronization can be guesstimated
  - Might be quite different from QCD in which case hadronization is a pure guess
    - E.g. SUEP, pure glue ➔ glueballs, etc.

- Decays of hadrons conclude the process
  - PYTHIA can implement but details must be entered by the user
    - New Pythia versions allow for full user control (and thus responsibility)
    - Older versions are often inaccurate except in very specific models

Snowmass: Setting up simulation to give dark jets

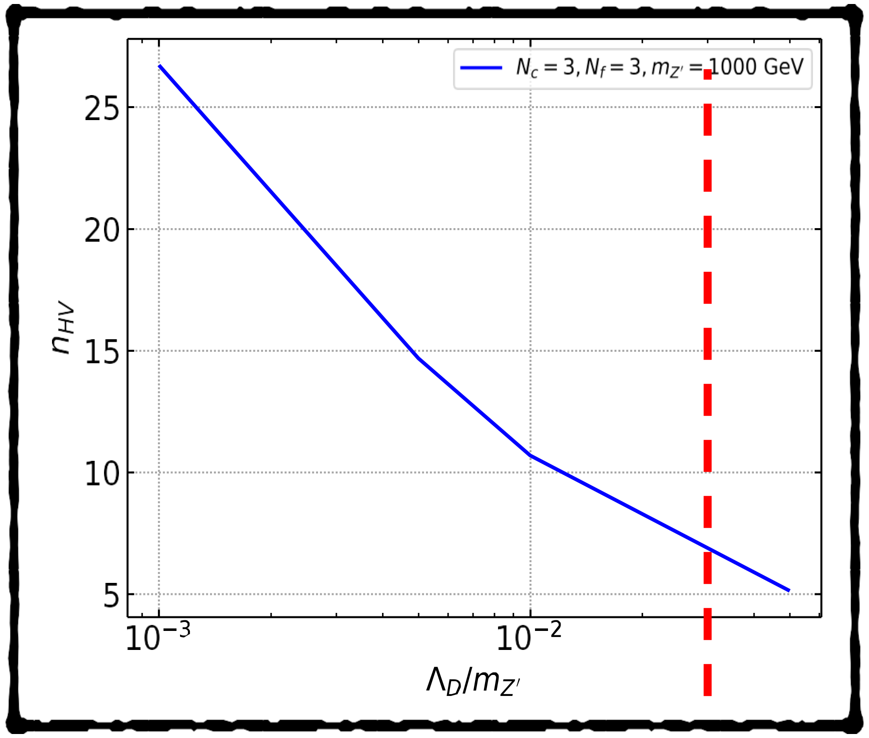
- Choose $N_{c_D} > 2$ and $N_{f_D} > 1, \Lambda_D > 1\,\mathrm{GeV}$ to avoid PYTHIA issues
- Pick $[0.25? <]$ $m_{\pi_D}/\Lambda_D < 2$ and set mass spectrum

Note: There are indications that the lower bound on m_π/Λ may not be needed; not confirmed yet

  - NB: This fixes the UV **current** quark mass m_{q_D} (not used in PYTHIA)
  - Set *constituent* quark mass 4900101:m0 via $m_{q_{const}} \equiv m_{q_D} + \Lambda_D$ (not an exact relation, should vary it)

- Pick $m_{Z'} \gtrsim 30\Lambda_D$ if you insist on having actual dark jets

Number of dark hadrons per Z' decay vs ratio of dark confinement scale to Z' mass



For now,

- Neglecting special treatment for flavor singlets
- Assuming baryons don't matter due to large mass

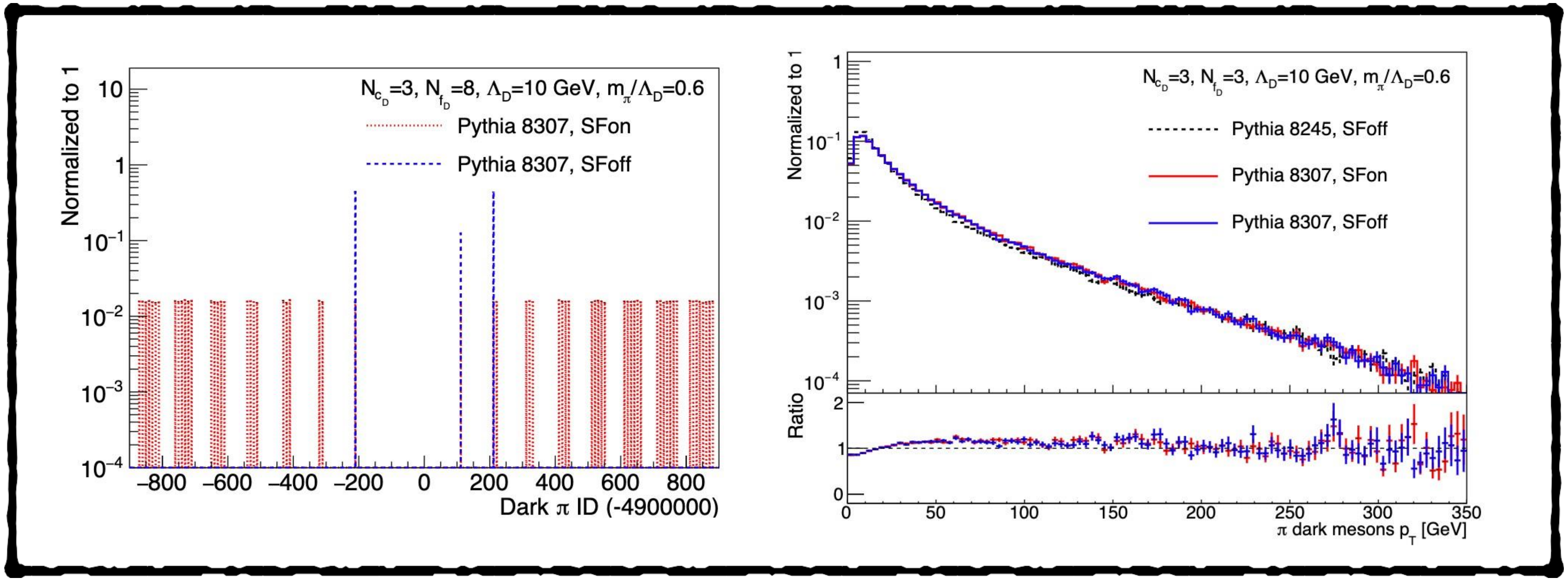
- Depending on m_{π_D}/Λ_D and portal, set the dark meson decay modes
  - Note: for $m_{\pi_D}/\Lambda_D < 1.53$, the $\rho_D \to \pi_D\pi_D$ mode is open!

PYTHIA8 improvements and validation

See also: Mies, Scherb, Schwaller arXiv:2011.13990

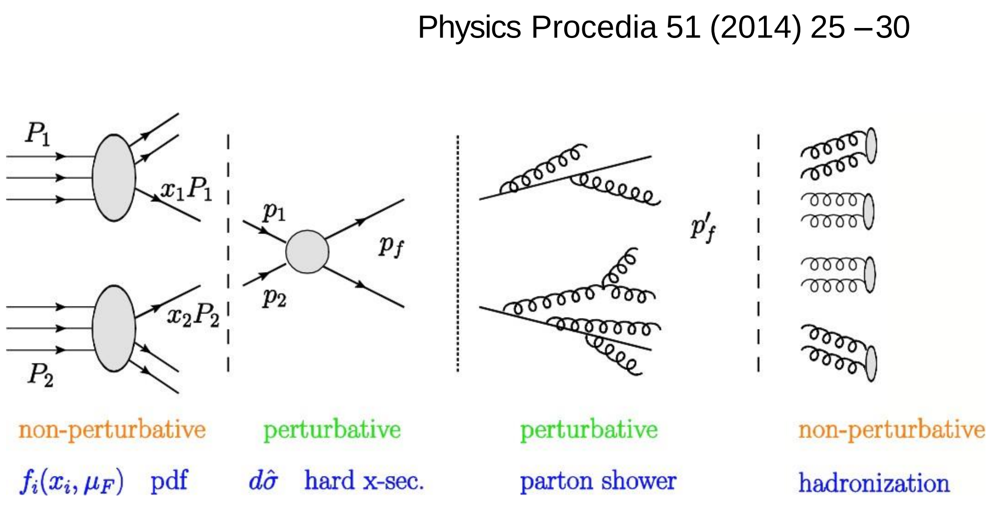
New PYTHIA8 HV module

- Allows user control of properties of individual quarks and hadrons (with separateFlav = on)
- Can simulate quarks with different masses
- But validated only for mass degenerate scenarios



- Tested to confirm it reproduces QCD: Snowmass darkshowers arXiv:2203.09503
- Adjustments in HV (mini)-string fragmentation fixed dark meson production at low pT
- Hadronization module not directly validated but reproduces SM QCD

Need for Improved Theory/Simulation

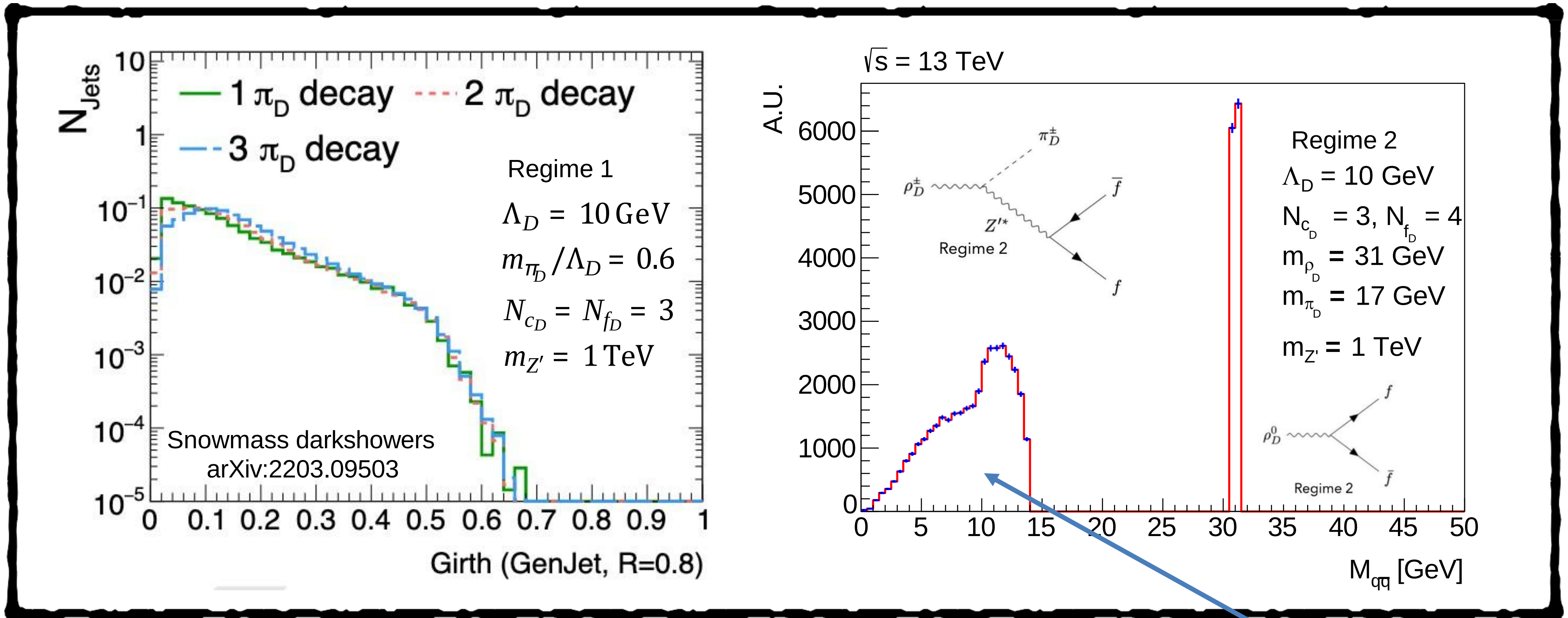


α_D runs, running controlled by Λ_D

- Heavy risk of simulating unphysical theories
  - Running of α_D , confinement scale Λ_D; hadron masses; need to understand how to correlate scales
  - Dependence of dark meson mass spectrum on UV quark masses

- Better theoretical understanding of space of signatures
  - Three body ρ_D decays were previous ignored, gets jet invisible fraction (r_{inv}) wrong
  - Phenomenology of spin - 0, 1 singlets not explored, may have unusual decays
- Understand limitations of the simulation tools
  - Development/ validation of new PYTHIA8$_{(8.307)}$ HV module for QCD-like theories only
  - Need to quantify dark hadronization uncertainties; limits predictions for substructure variables

Impact on SM final states



$\rho \rightarrow \pi\pi$

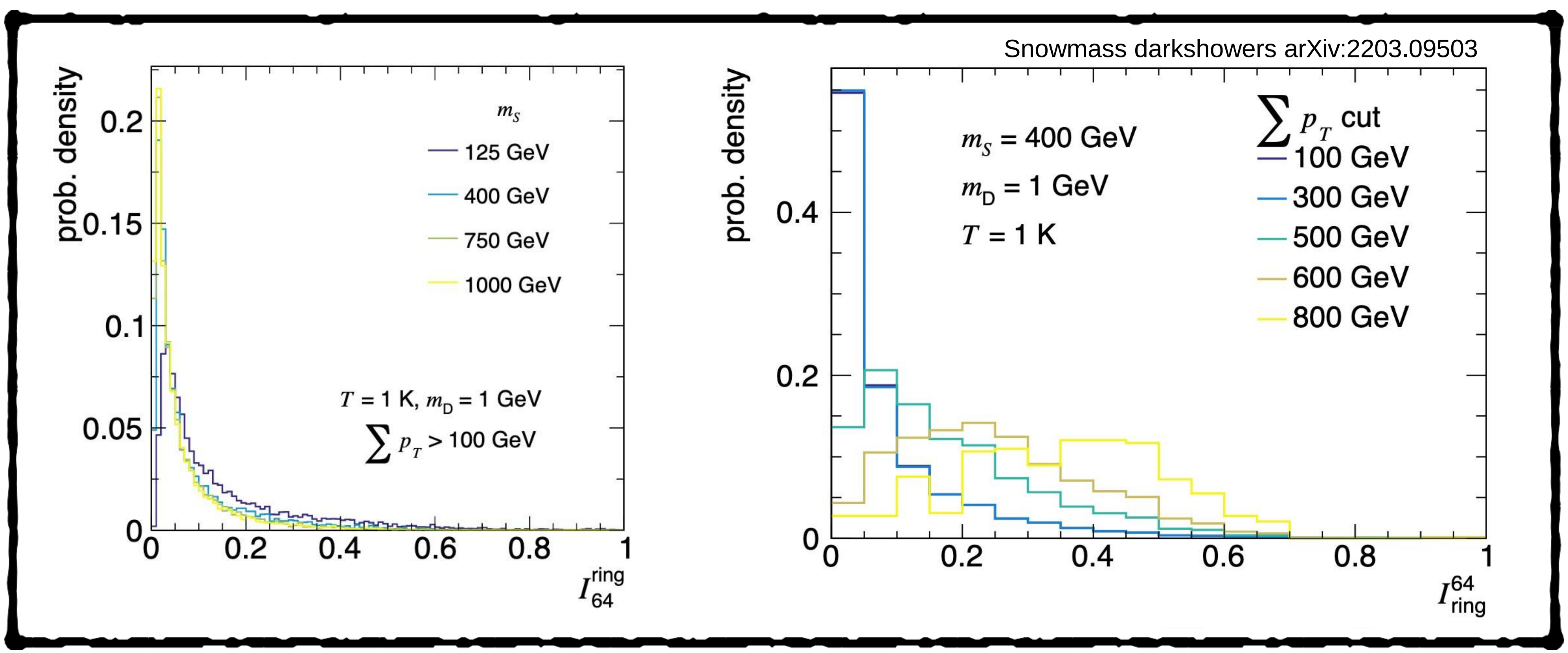
Regime 1:	→	open
Regime 2:	→	closed

This affects r_{inv}

- Unfortunately Snowmass studies were badly time-limited.
- Focus on large-R-jet substructure analysis for one regime-1 benchmark with $\Lambda_D = 10\,\mathrm{GeV}$
- Number of decaying pions can lead to differences in jet substructure (but hard to make a statement without studying QCD background)
- Potentially different kinematics for regime 2 scenarios, not yet explored
- One jet substructure variable (pT_D) that was used in an SVJ BDT is not IRC safe,
- *this is very dangerous as it can become the tail that wags the dog, and does so incorrectly.*

Beyond QCD-like theories: SUEP

- Large $\alpha_D N_{c_D}$: in UV: unsuppressed large- angle radiation → wide, spherical showers.
  Note: only a small class of theories are known to exist, none realistic
- No dedicated simulation tools, at best some idealised approximations
- Experimental avenues being investigated; care in use of simulations, triggers necessary
- Common signature is global radiation pattern, high track multiplicity;
  track counting, event shape observables can serve as useful analysis tool
- New variables to quantify event isotropy for SUEP benchmark models:



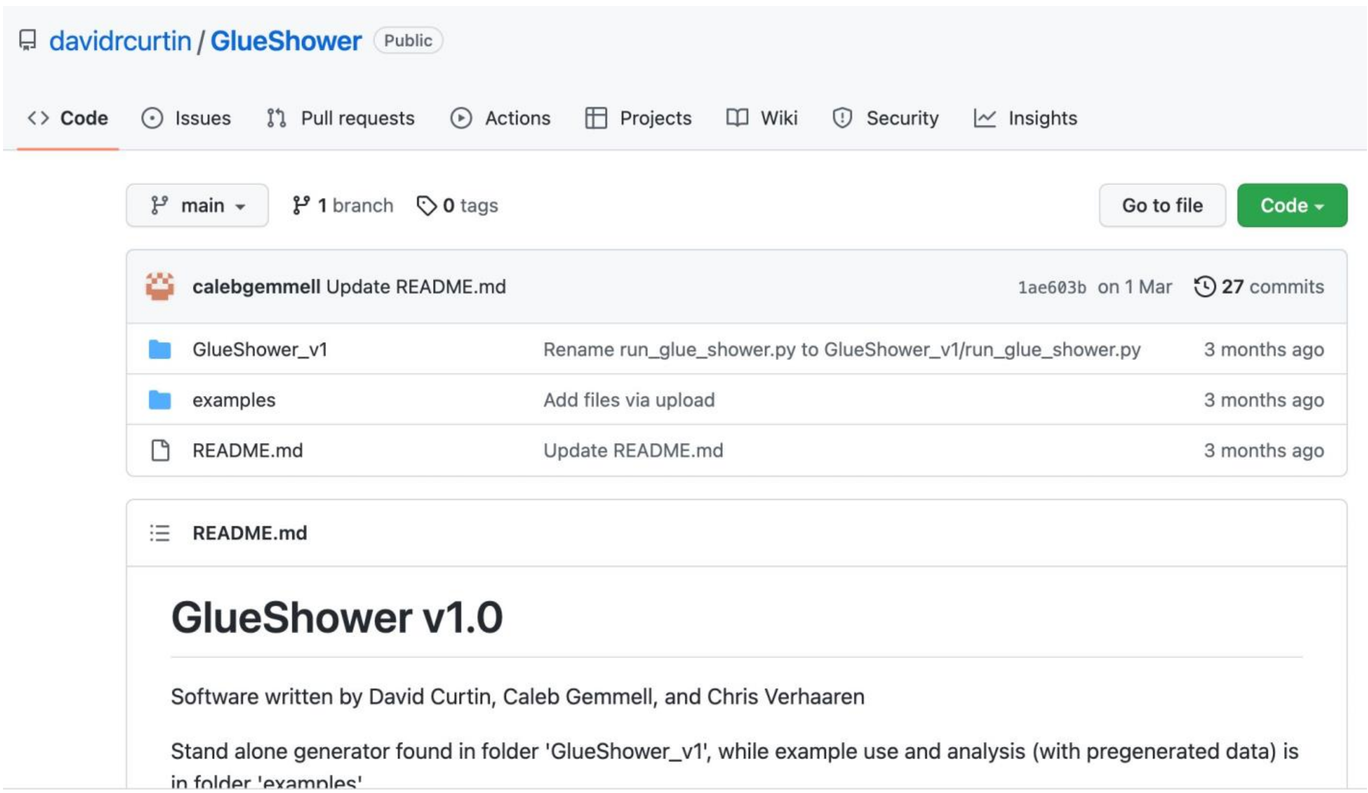
Beyond QCD-like theories: Glueballs

- If no low-mass dark quarks (or scalars) then confinement scale involves only dark gluons.
- Dark glueballs: bound states of gluons. Complex spectrum computed on lattice
- Showering is straightforward, hadronization is not!
- No data to match these theories to; hadronization unknown and unlikely to be similar to QCD
- Recent first effort for creating Yang-Mills hadronization

Curtin, Gemmell, Verhaaren
arXiv:2202.12899

- Publicly available simulation tool, with two different hadronization settings
  - Perturbatively motivated jet-like hadronization
  - Non-perturbative string back-reaction, giving more exotic final state

Warning: there's a lot of guesswork here!



Some Additional Comments for Today

Not studied:

- LLPs: strong effort underway

  But what if each jet mixes prompt, LLP and MET (as in QCD)? Will searches fail?

- Many other non-QCD-like theories, mediators – what other signatures are we missing?

  i.e. if searches target the theories discussed here, what will we **not** be sensitive to?

- Hadronization uncertainties – how can we parametrize our deep ignorance?

Challenge of too many theories, parameters?

- Is it possible to use a “simplified model” approach? Problem of modeling hadronization.

Connection between LHC and DM signals

- Possible in individual models, but there is **never** a 1-to-1 map
- MET may be DM or it may not be; DM is MET, but may not dominate it
- What’s the best approach to avoid misleading ourselves and others?

Conclusions

- Strongly interacting dark sectors can explain a variety of SM shortcomings and present interesting opportunities at the experiments
- Phenomenological and experimental program strong but needs expansion
- The dark showers snowmass project
  - surveyed existing models, constraints for QCD-like theories with semivisible, emerging jets
  - overhauled and validated PYTHIA8$_{(8.307)}$ HV module with more realistic spectra and increased control on dark mesons properties, took first steps towards understanding substructure variables
  - set guidelines for consistent UV to IR physics for QCD-like theories
  - surveyed new analysis strategies to identify new strongly interacting physics at colliders
  - discussed beyond-QCD-like scenarios including SUEPs and glueballs
- A successful exploration of strongly interacting sectors benefits from understanding the theories in UV and IR, and is further complemented by lattice simulations
- Future exploration of strongly interacting scenarios is a community exercise, will need lattice, (SM) QCD, LLP, DM experts and experimentalists working together

A HUGE THANK YOU TO ALL CONTRIBUTORS OF THE SNOWMASS PAPER

Backup

Free parameters in QCD-like theories

- Let us consider QCD-like SU(N$_D$) gauge theories with N_{f_D} mass degenerate Dirac fermions (in fundamental representation)
  - Two continuous free parameters: (current) quark mass, gauge coupling $\alpha_D(\mu)$ (similar to $\alpha_s(\mu)$)
- This theory produces bound states in the form of pions, rho etc.
- In particular, for N_{f_D} flavours we get $N_{f_D}^2 - 1$ number of mass degenerate pions and rho mesons
- The exact mass spectrum of bound states is computed by lattice
  - Side remark: lattice does not know 'units', so the masses predicted by lattice are always some dimensionless numbers
  - Means we need to choose one dimensionful number to convert them to physical masses
  - Dimensionful number $\rightarrow \Lambda_D$, scale where α_D diverges
  - Theory has only four free parameters $\Lambda_D, m_{\pi_D}/\Lambda_D, N_{c_D}, N_{f_D}$; m_{π_D}/Λ_D proxy for quark mass

Side remark: In the SM $\Lambda \sim \mathcal{O}(300)\text{MeV}, \quad \frac{\text{m}_\pi}{\Lambda} \sim 0.5$

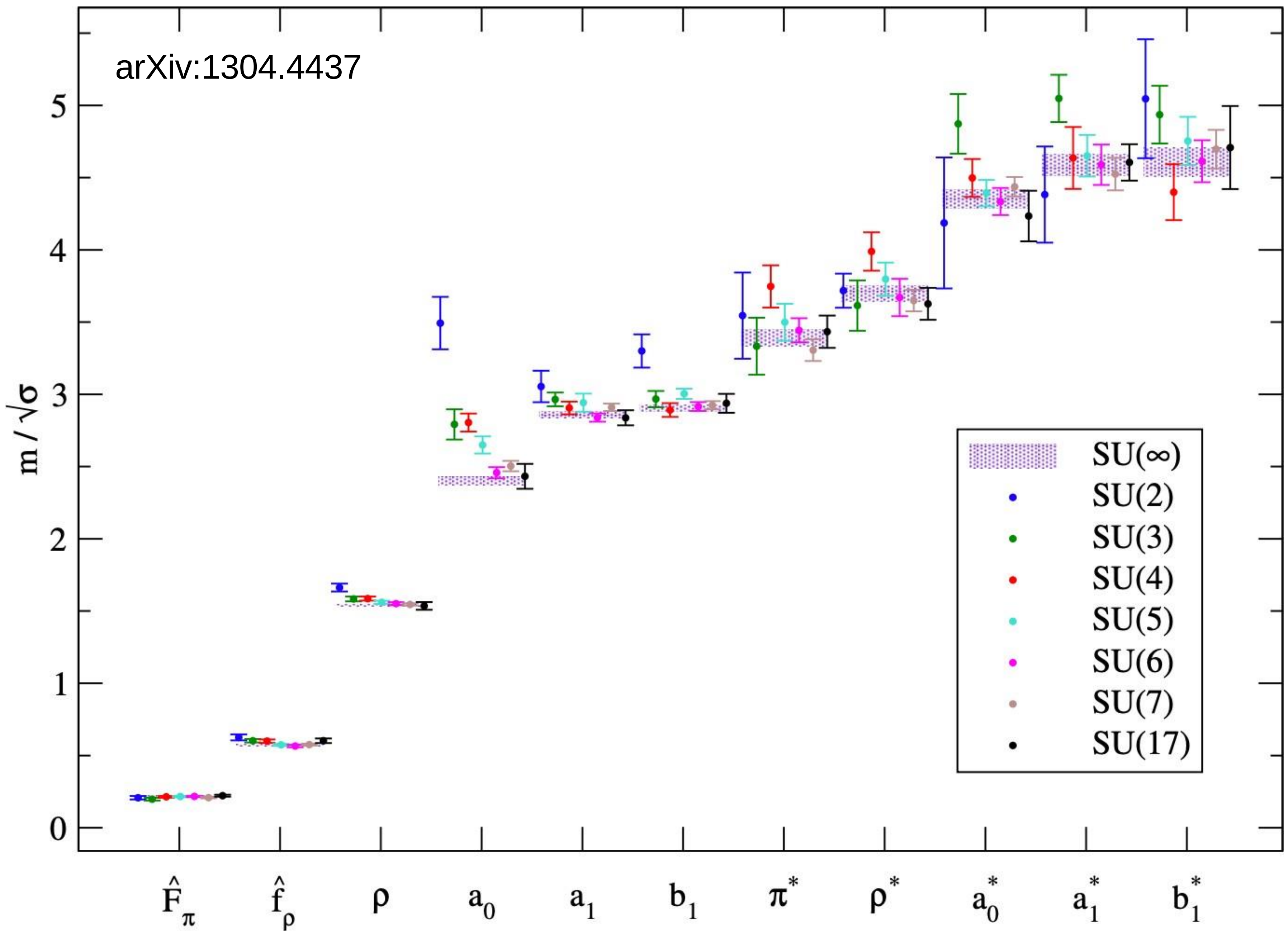
‘Hacking’ branching ratios in PYTHIA

- For a theory with N_f flavors, number of pions are $N_f^2 - 1$
- Mass degenerate quarks imply mass degenerate pions (and rho)
- Out of these $N_f - 1$ are diagonal pions and $N_f(N_f - 1)/2$ off-diagonal pions
- Pythia models these diagonal and off-diagonal states using three pions, pythia assigns three pdg codes for these, one for diagonal, one for upper triangle and one for lower
- The number of pions/rhos that can decay depends on the specific theory
- Thus, one should rescale branching ratio of the pions by their multiplicity to account for the probability of decay
- If number of diagonal pions decay then the rescale factor is $x/(N_f - 1)$
- Similarly for number of off-diagonal pions decaying the probability is $y/(N_f(N_f - 1)/2)$

$$\Pi = \begin{bmatrix} \pi_D^0 & \pi_D^\pm & \cdots \\ \vdots & \ddots & \\ \pi_D^\pm & & \pi_D^0 \end{bmatrix}$$

Meson masses

- Lattice simulations for a large number of (large N) SU(N) theories show that meson masses are more or less independent of the gauge group dimension



PYTHIA8 HV settings

- Choose $m_{Z'} \gtrsim 30\Lambda_D$ to get jets
- Choose $N_{c_D} > 2, N_{f_D} > 1$
- Choose $0.25 < m_{\pi_D}/\Lambda_D < 2$ to set mass spectrum using lattice fits
  - NB: This mass spectrum will provide current quark mass (NOT the same as PYTHIA8 HV 4900101:m0 parameter
- Set constituent quark mass 4900101:m0 as $m_{q_{const}} \equiv m_{q_D} + \Lambda_D$ (this is not an exact relation)
- Set branching ratios as predicted by theory model

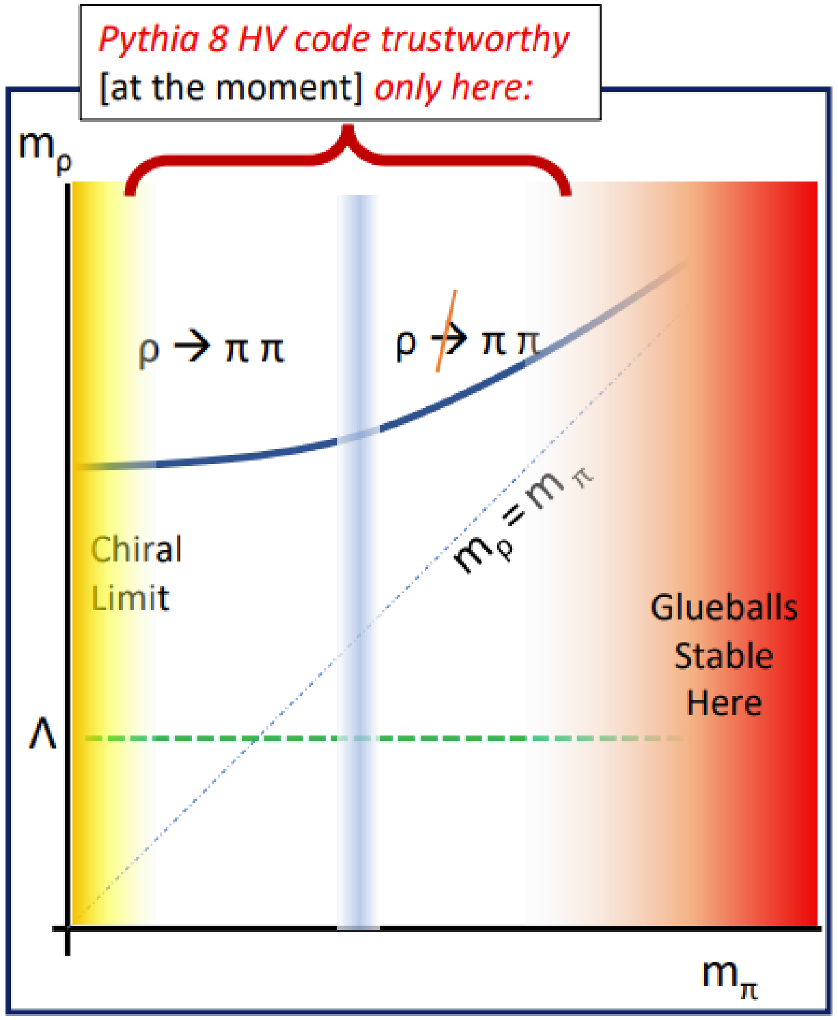


Fig. M. Strassler

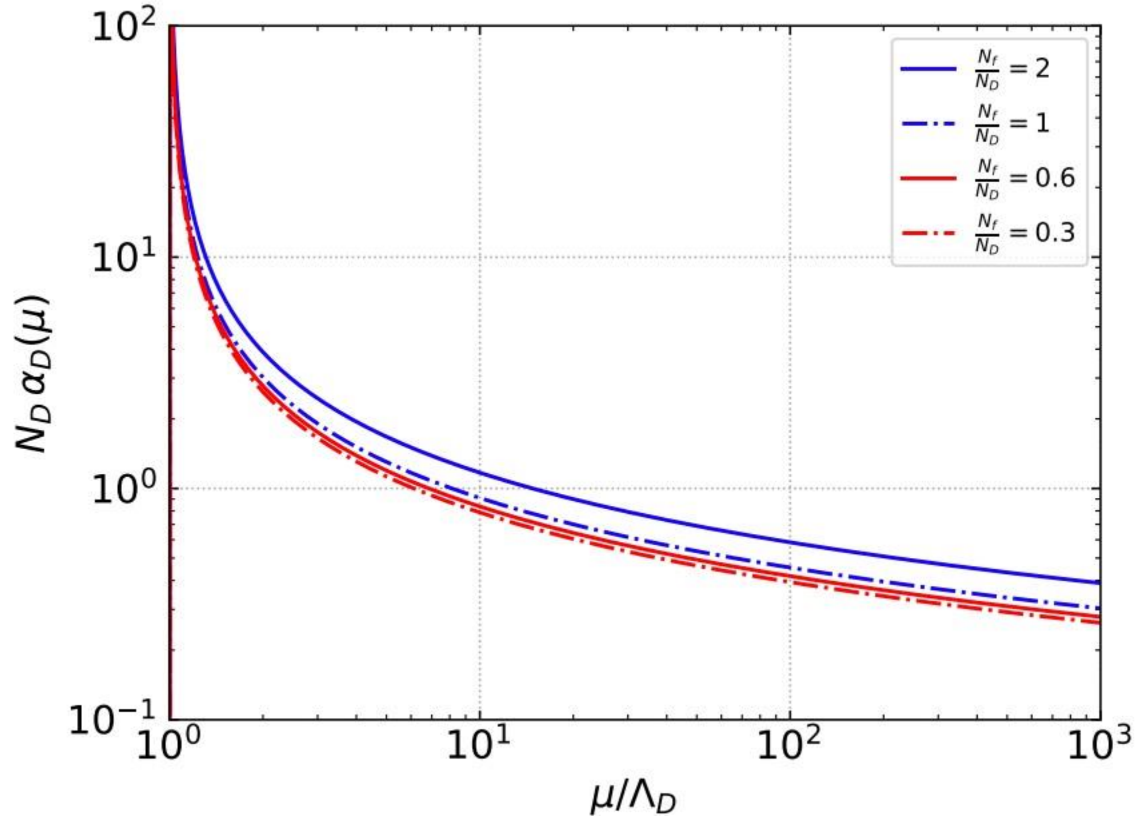
Note: there is some recent indication that the lower bound in the plot above can be relaxed; this is both a theory question and a question of whether Pythia's hadronization module can handle it.

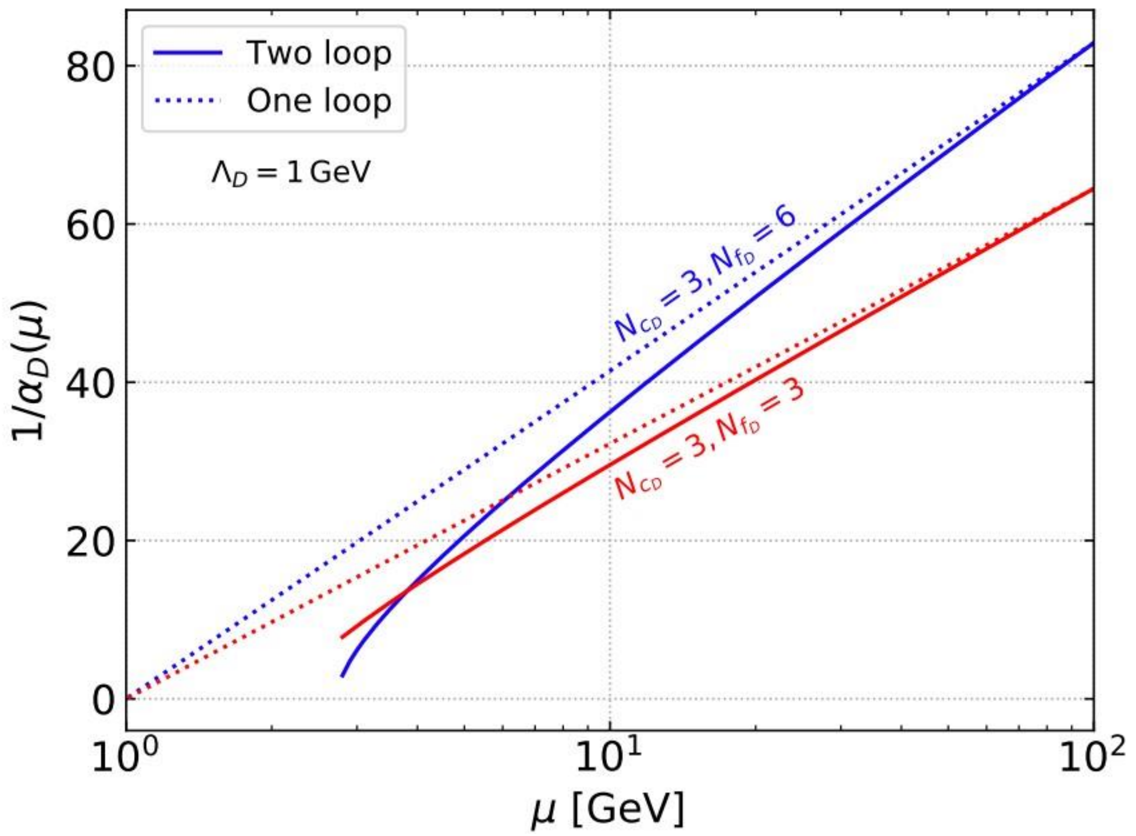
Benchmarks

- A few suggested first list of benchmarks in snowmass v1, minor improvements in v2 foreseen
- Applicable for s-channel vector mediated SM - DS interactions

Regime	N_{c_D}, N_{f_D}	Λ_D [GeV]	**Q**	m_{π_D} [GeV]	m_{ρ_D} [GeV]	Stable dark hadrons	Dark hadron decays
$m_{\pi_D} < m_{\rho_D}/2$	3,3	5	Various	3	12.55	$0/1/2\pi_D^0$	$\rho_D^{0/\pm} \to \pi_D^{0/\pm}\pi_D^{\mp}$ $\pi_D^0 \to c\bar{c}$
	3,3	10	Various	6	25	$0/1/2\ \pi_D^0$	$\rho_D^{0/\pm} \to \pi_D^{0/\pm}\pi_D^{\mp}$ $\pi_D^0 \to c\bar{c}$
	3,3	50	Various	30	125.5	$0/1/2\ \pi_D^0$	$\rho_D^{0/\pm} \to \pi_D^{0/\pm}\pi_D^{\mp}$ $\pi_D^0 \to b\bar{b}$
$m_{\pi_D} > m_{\rho_D}/2$	3,4	10	(-1,2,3,-4)	17	31.77	All π_D	$\rho_D^0 \to q\bar{q}$ $\rho_D^{\pm} \to \pi_D^{\pm} q\bar{q}$

Running of α_D





- Running depends on N_{f_D}/N_{c_D}
- Two loop corrections become important as N_{f_D}/N_{c_D} increases

Non-Abelian theories characterisation

- Restricted our thinking about new SU(N) gauge group uncharged under the SM
- Theories traditionally characterised by N_{c_D}, N_{f_D}, Λ_D, α_D, m_{q_D} together with mediator mass and couplings in UV and m_{π_D}, m_{ρ_D}, m_{baryon_D} corresponding branching ratios, lifetimes in IR

Different regimes in signature space

This is a continuum!

Theories that make (dark) jets (QCD-like)
$\alpha_D N_{c_D}$ small

Theories that instead make Soft Unclustered Energy Patterns (SUEPs)
$\alpha_D N_{c_D}$ large

This refers to the coupling constant evaluated in the showering regime