Darkshowers – snowmass whitepaper

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

Snowmass 2021

NAWI Graz
Natural Sciences

FWF
Der Wissenschaftsfonds.

UNI
GRAZ

Snowmass darkshowers

- The snowmass darkshowers group was formed during the snowmass process and began of course with formation of the most 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

DarkShowers-Snowmass2021

Enter your search term

May 2022

12 May Dark showers snowmass project meeting on EF10 TG report

February 2022

24 Feb Dark showers snowmass project meeting

10 Feb Dark showers snowmass project meeting

January 2022

27 Jan Dark showers snowmass project meeting

13 Jan Dark showers snowmass project meeting

December 2021

09 Dec Dark showers snowmass project meeting

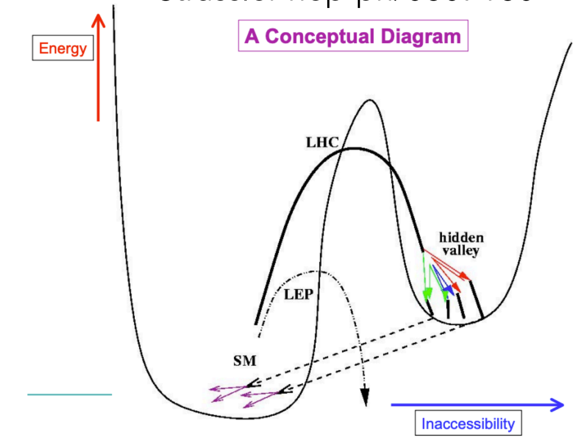
November 2021

18 Nov Dark showers snowmass project meeting

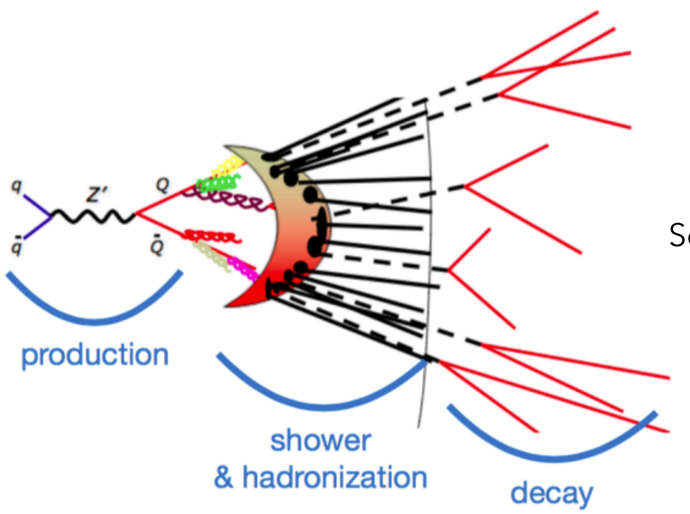
New physics: where art thou?

(Light) new physics could still be hiding in SM extensions with non-Abelian gauge groups (aka Hidden Valleys)

Strassler hep-ph/0607160



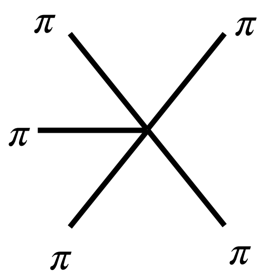
New previously unexplored signatures

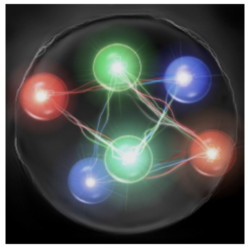


Strassler & Zurek
hep-ph/0604261
Cohen, Lisanti, Lou
arXiv:1503.00009
Schwaller, Stolarski & Weiler
arXiv:1502.05409
LLP community report
arXiv:1903.04497

Diagram by M. Strassler

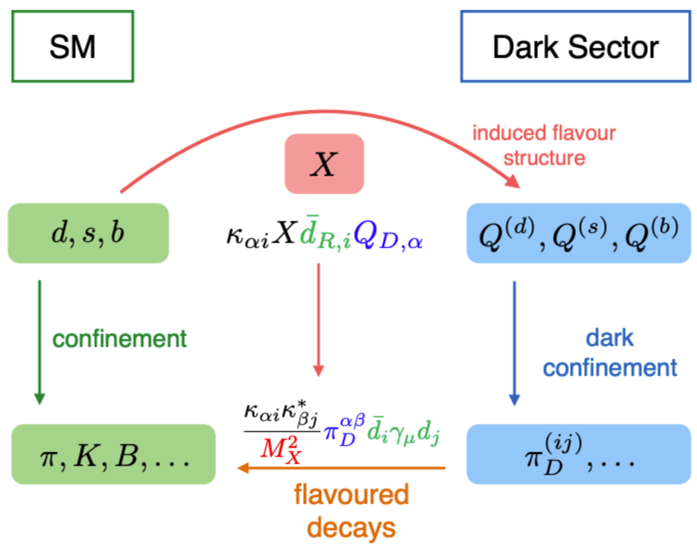
New dark matter candidates





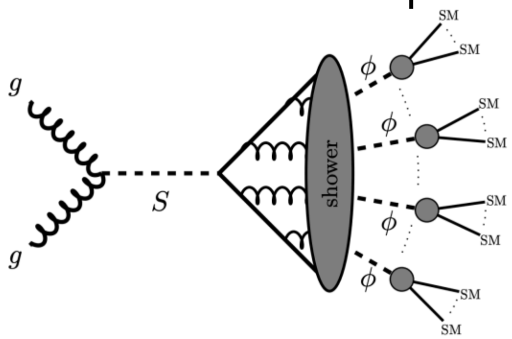
Hochberg, Kuflik, Murayama
arXiv:1512.07917
See also
Kribs & Neil
arXiv: 1604.04627

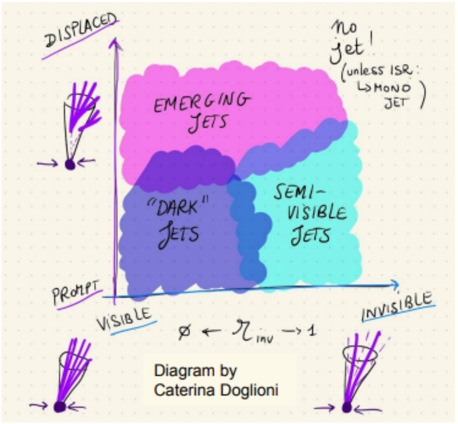
Connections with flavour physics



Schwaller and Renner
arXiv:1803.08080

Rich and complex signature space





Hofman and Maldacena
arXiv:0803.1467
Strassler arXiv:0801.0629
Knapen, Griso, Papucci, Robinson
arXiv:1612.00850

Non-Abelian theories characterisation

- Only thinking about new SU(N) gauge group uncharged under the SM
- Theories traditionally characterised by $N_{c_D}, N_{f_D}, \Lambda_D, \alpha_D, m_{q_D}$ together with mediator mass and couplings in UV and $m_{\pi_D}, m_{\rho_D}, m_{baryon_D}$ corresponding branching ratios, lifetimes in IR

Few different regimes in signature space

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

Theories don't make (dark) jets
They make
Soft Unclustered Energy Patterns (SUEPs)
$\alpha_D \, N_{c_D}$ large

Event shapes in between

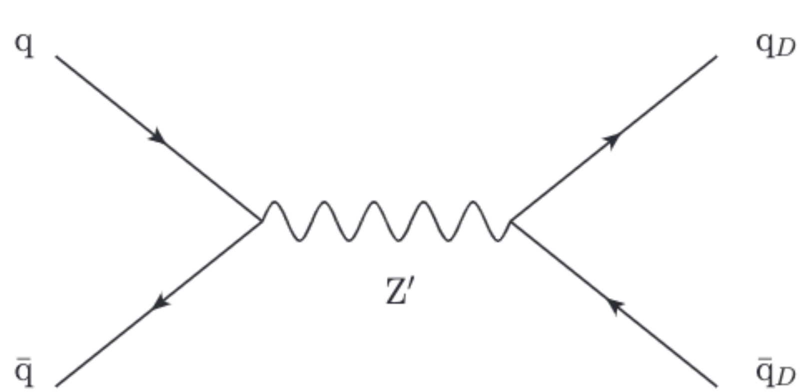
Theories with dark jets

- Traditionally signature based approach: $N_{c_D}, N_{f_D}, \Lambda_D, \alpha_D, m_{q_D}, m_{\pi_D}, m_{\rho_D}, m_{baryon_D}$ branching ratios along with mediator properties free variables
- Two primary portal analysis s-channel Z' and t-channel bifundamental ϕ
- Signature space with semivisible jets, emerging jets, trackless jets
- Treat dark rho and dark pions on same footing
- Simulation based on 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

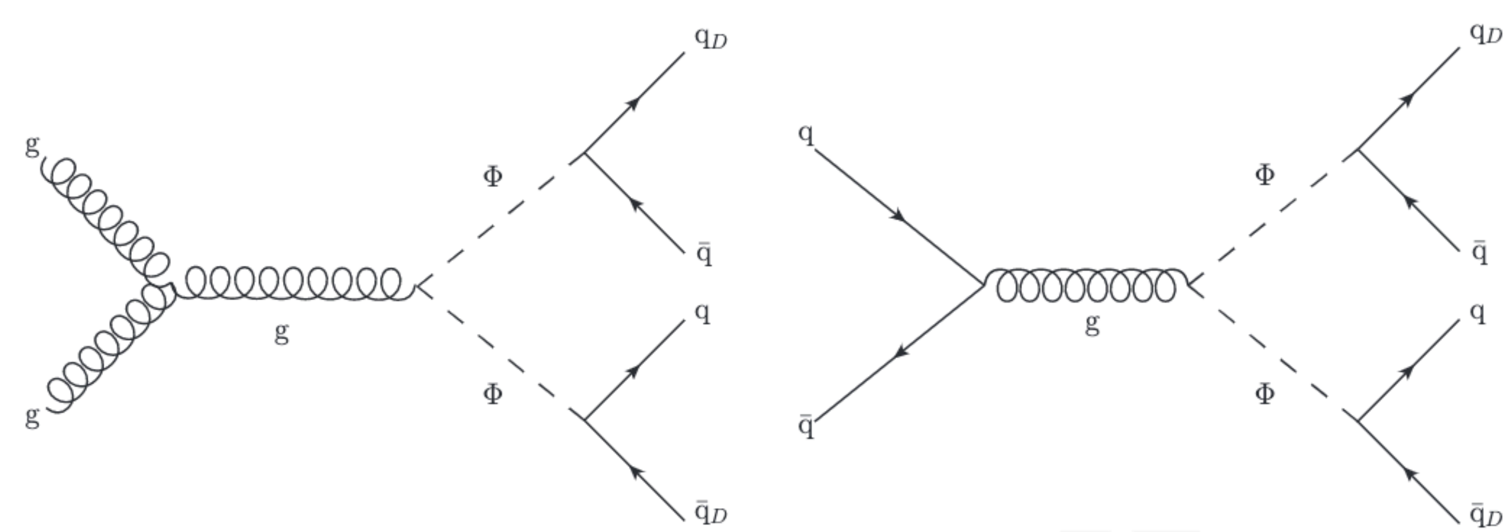
s-channel (Z') production

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



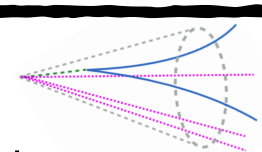
t-channel (bifundamental) production

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



LHC phenomenology

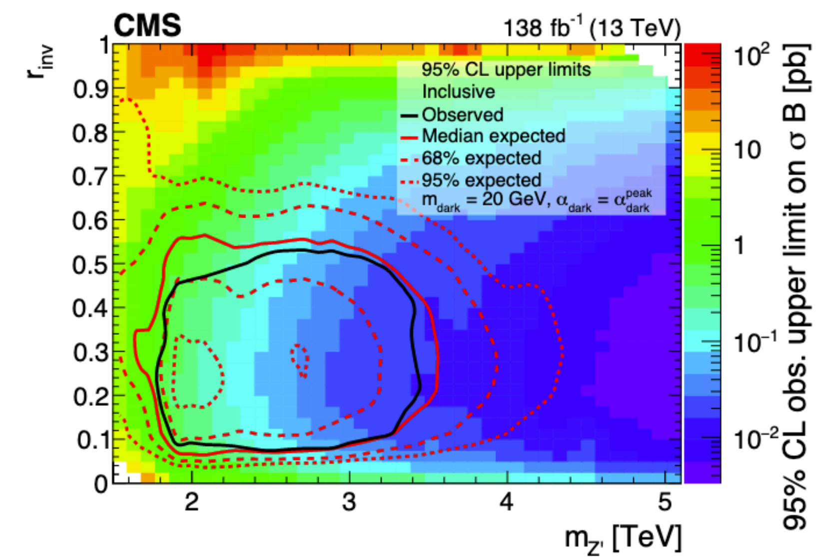
Semivisible jets



- Unstable dark mesons decay promptly via two body decays
- $r_{inv} = N_{stable}/(N_{stable} + N_{unstable})$

Cohen, Lisanti, Lou
arXiv:1503.00009

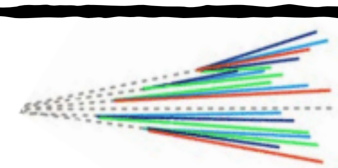
- Small r_{inv}: dijet search strategy;
  Large r_{inv}: monojet searches;
  Intermediate r_{inv}: Dedicated searches



CMS collaboration
arXiv:2112.11125

First experimental for semivisible jets

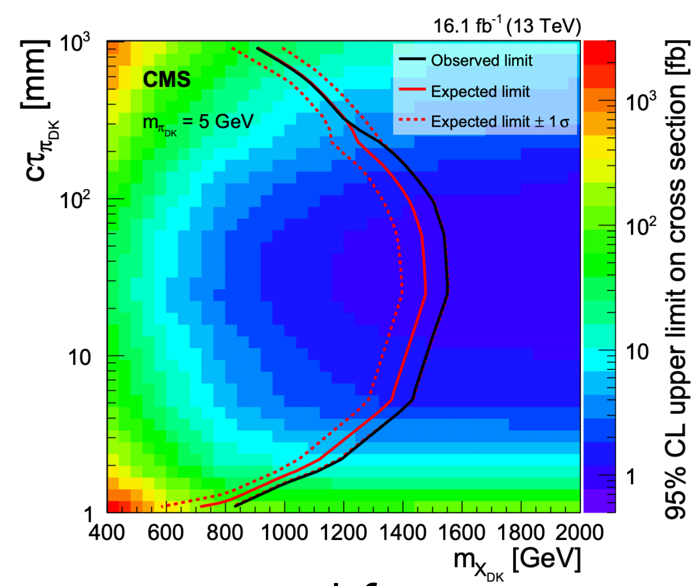
Emerging jets



- Dark mesons with finite lifetime: jet with multiple displaced vertices
- Unflavoured case: one lifetime for all dark hadrons

Schwaller, Stolarski & Weiler
arXiv:1502.05409

- Flavoured case: diagonal, off-diagonal dark hadrons have different lifetime



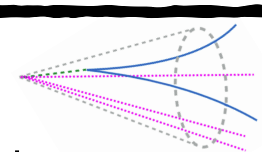
CMS collaboration
arXiv:1810.10069

First experimental for emerging jets

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

LHC phenomenology

Semivisible jets



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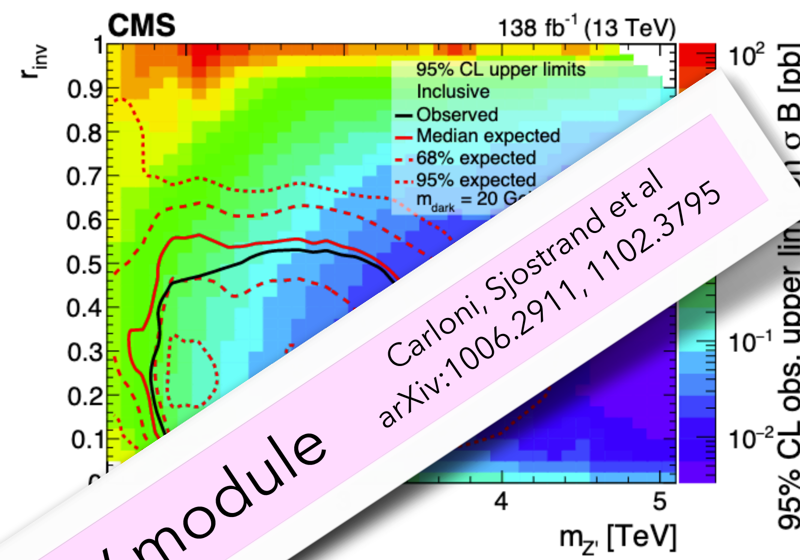


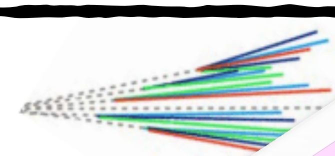
CMS collaboration
arXiv:2112.11125

imental for semivisible jets

All studies use PYTHIA8$_{(<8.307)}$ HV module

Carloni, Sjostrand et al
arXiv:1006.2911, 1102.3795

Emerging jets



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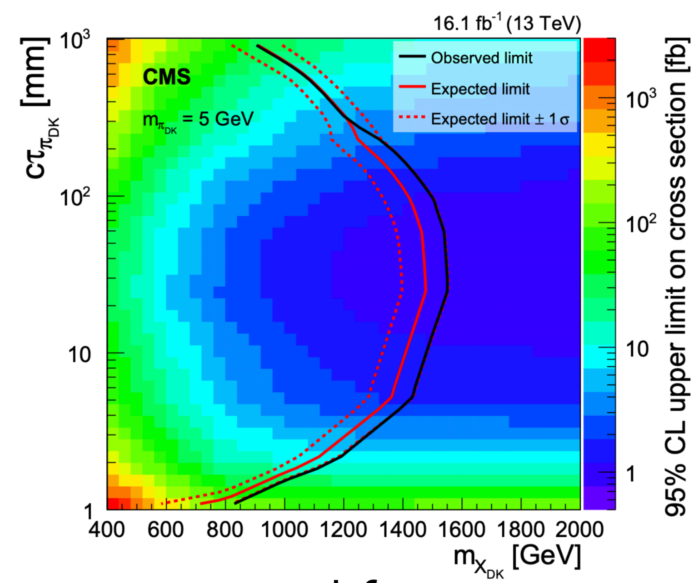


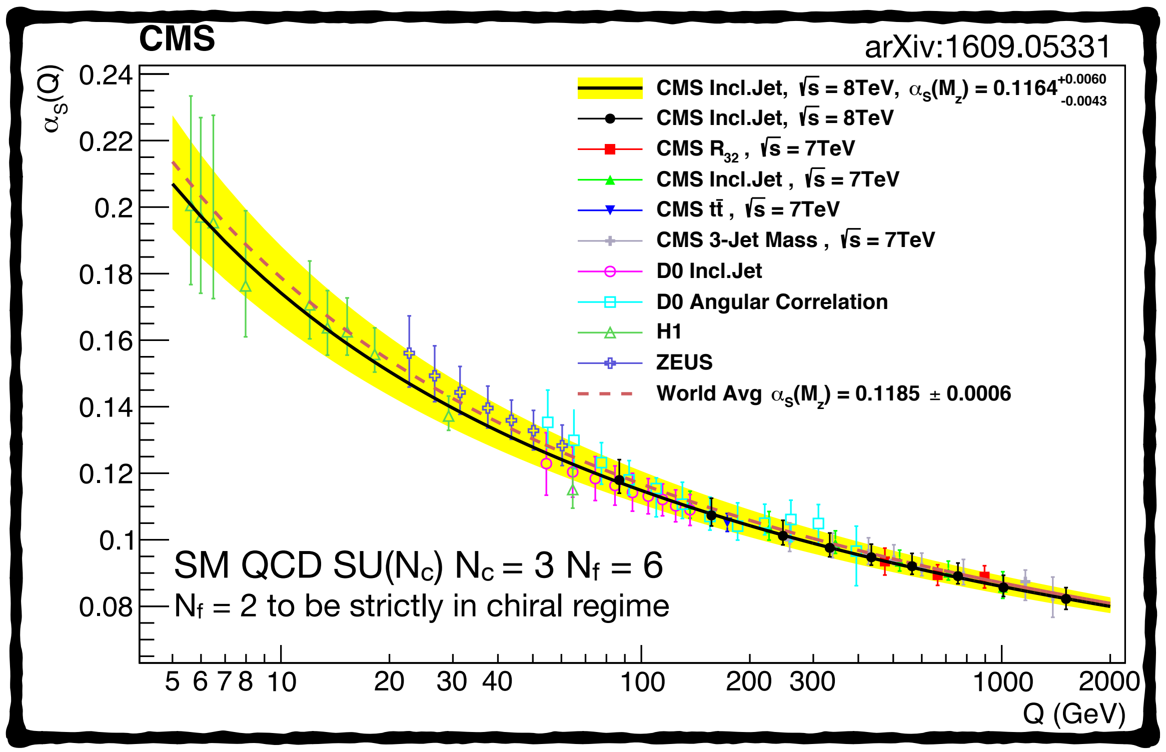
CMS collaboration
arXiv:1810.10069

First experimental for emerging jets

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

A further insight into QCD-like theories

- For mass degenerate fermions theory has four free parameters $N_{c_D}, N_{f_D}, m_{\pi_D}/\Lambda_D, \Lambda_D$
- Couple via s-channel Z' mediator



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

arXiv:2008.12223

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

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

See also talk by M. Strassler at LLPX

Mass spectrum

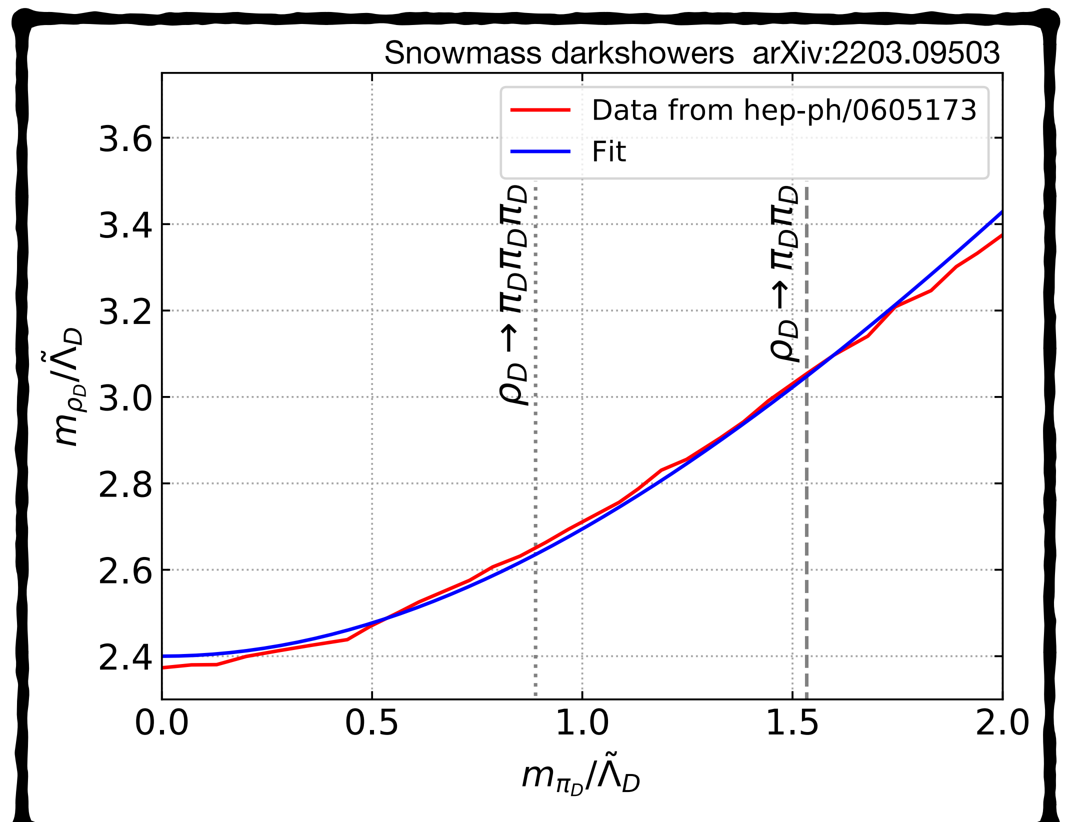
- $SU(Nc_D), Nc_D > 2$ theory with N_{f_D} mass degenerate quarks has $N_{f_D}^2 - 1$ mass degenerate dark rho, pions, plus 1 spin -0 and spin -1 singlet

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

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

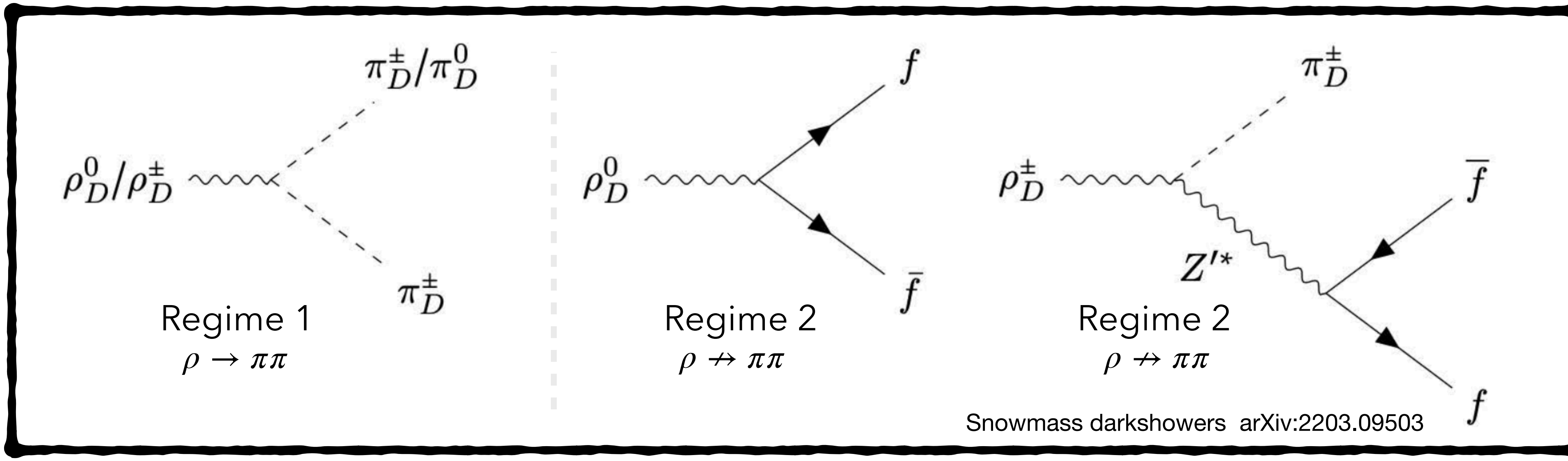
$$\frac{m_{\pi_D}}{\tilde{\Lambda}_D} = 5.5\sqrt{\frac{m_{q_D}}{\tilde{\Lambda}_D}} \qquad \frac{m_{\rho_D}}{\tilde{\Lambda}_D} = \sqrt{5.76 + 1.5\frac{m^2_{\pi_D}}{\tilde{\Lambda}^2_D}}$$

- Pick $0.25 < m_{\pi_D}/\Lambda_D < 2$ to set mass spectrum
- Pick $m_{Z'} \gtrsim 30\Lambda_D$ to get jets
- Neglect special treatment for singlets for now
- Assume baryons don't matter due to their large mass



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!)

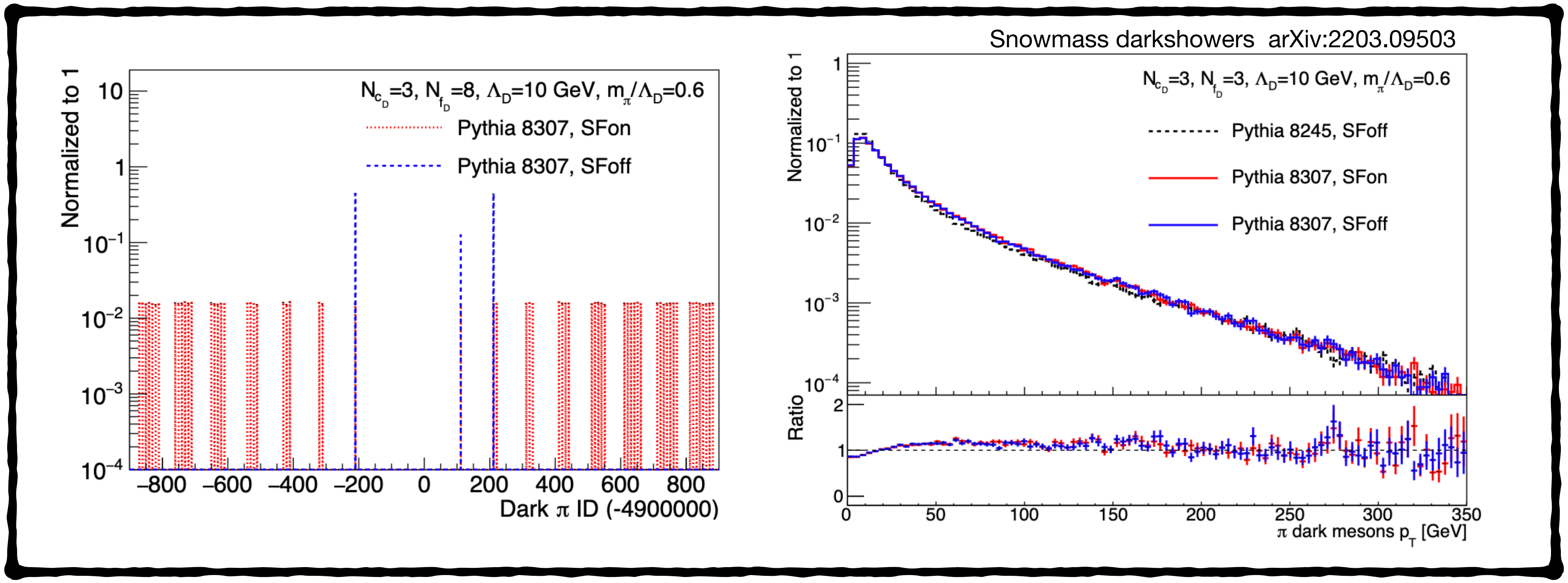
See also Beriln, Blinov, Gori, Schuster, Toro arXiv:1801.05805

  - 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

PYTHIA8 improvements and validation

See also:
Mies, Scherb, Schwaller
arXiv:2011.13990

- Need to be able to control properties of individual hadrons in PYTHIA8 HV
- How should such mass degenerate dark quark theories look like in MC simulation?
- Do we reproduce SM QCD using PYTHIA8 HV module?

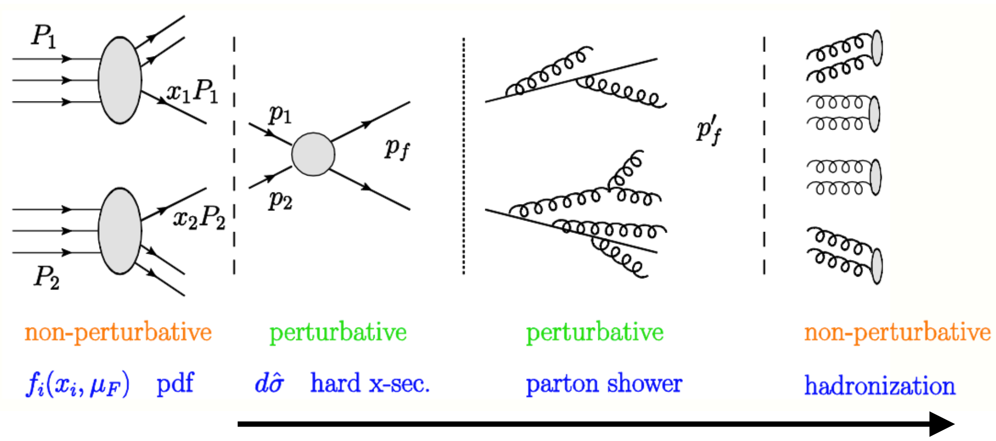


Pythia8.307
now available

- Adjustments in HV (mini)-string fragmentation so that it leads dark meson to p_T suppression to match with SM QCD; now available in PYTHIA8$_{(8.307)}$
- PYTHIA8$_{(8.307)}$ now has possibility to separately control properties of dark quark and mesons (separateFlav = on)
- Validated only for mass degenerate scenarios
- Hadronization module not validated however it reproduces SM QCD in appropriate regime

Why should we care?

Physics Procedia 51 (2014) 25 - 30

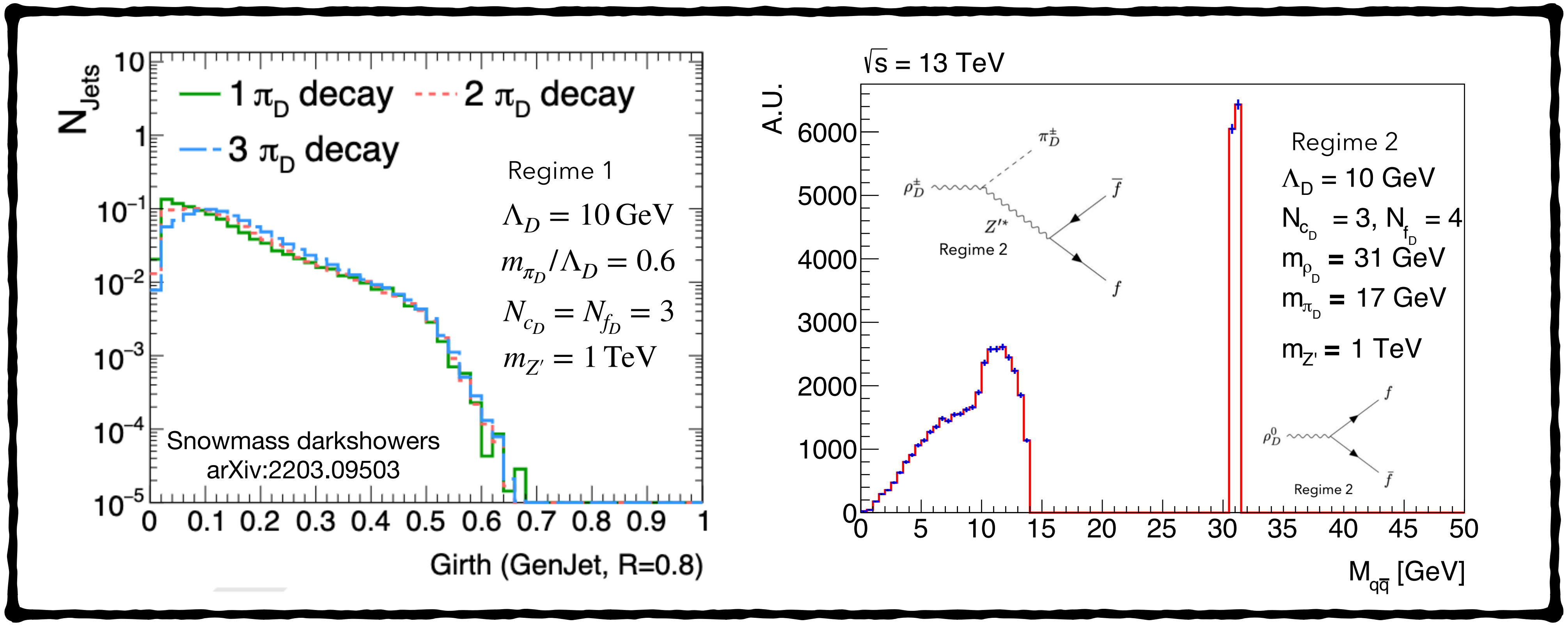


α_D runs, running controlled by Λ_D

- We run the risk of simulating unphysical theories
  - α_D runs within jetty physics range, provides reference scale Λ_D; need to understand how to correlate scales
  - Dark meson mass spectrum dependent on dark quark masses; quantities in IR result from UV physics
- Quantify dark hadronization uncertainties, which may limit the predictive power for substructure variables

- Classify signature parameter space
  - Three body ρ_D decays are not previously captured
  - Phenomenology of spin - 0, 1 singlets not explored
- Understand limitations of the simulation tools
  - Development and validation of new PYTHIA8$_{(8.307)}$ HV module possible because we can understand physics
- Develop first principles understanding
- Correlate physical phenomenon e.g. dark matter signature cross correlation

Impact on SM final states

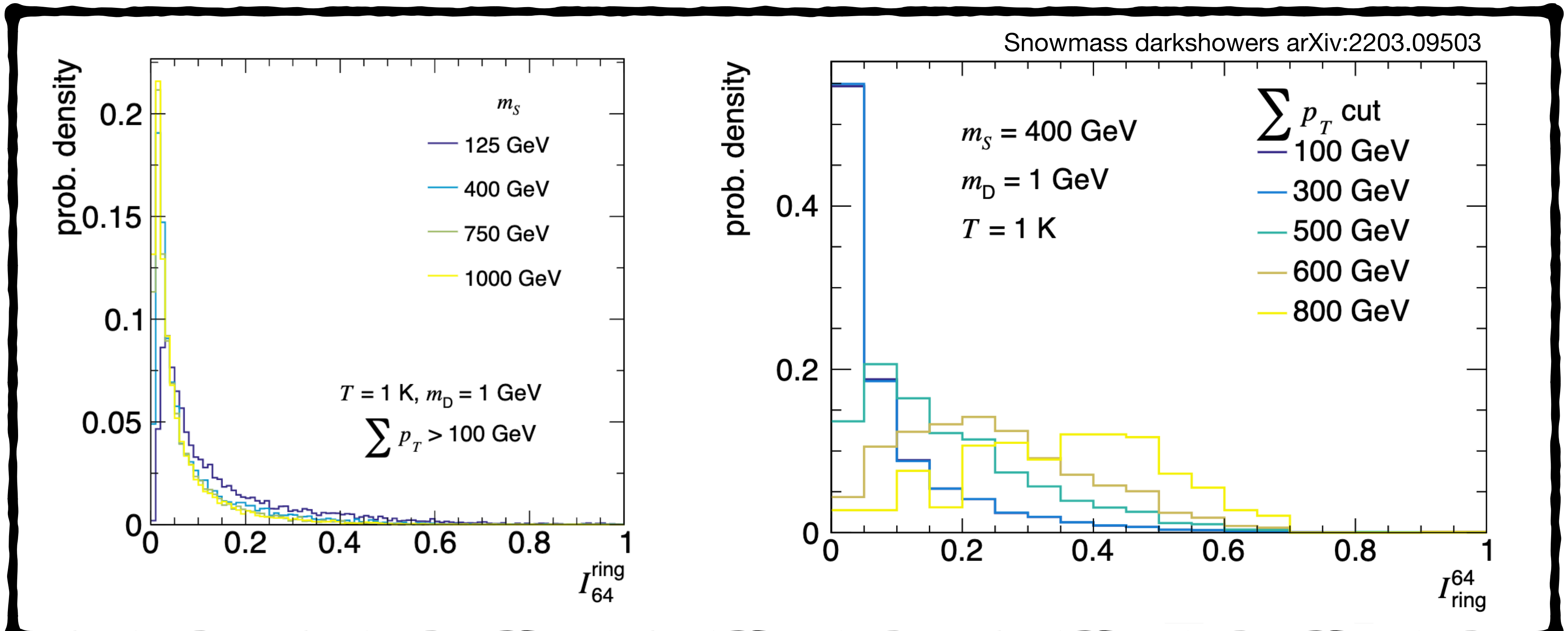


Regime 1: $\rho \to \pi\pi$ open
Regime 2: $\rho \to \pi\pi$ closed

- Studies currently concentrate on regime - I
- Focus on large R jet substructure analysis for one benchmark with $\Lambda_D = 10\,\mathrm{GeV}$
- Number of decaying pions can lead to differences in jet substructure variable potentially in region of interest for BDT but hard to make a statement without studying QCD background
- Potentially different kinematics for regime - II scenarios, not yet explored
- Some of the jet substructure variables (e.g. pT_D) are not be IRC safe, care should be taken while using them

Beyond QCD-like theories: SUEP

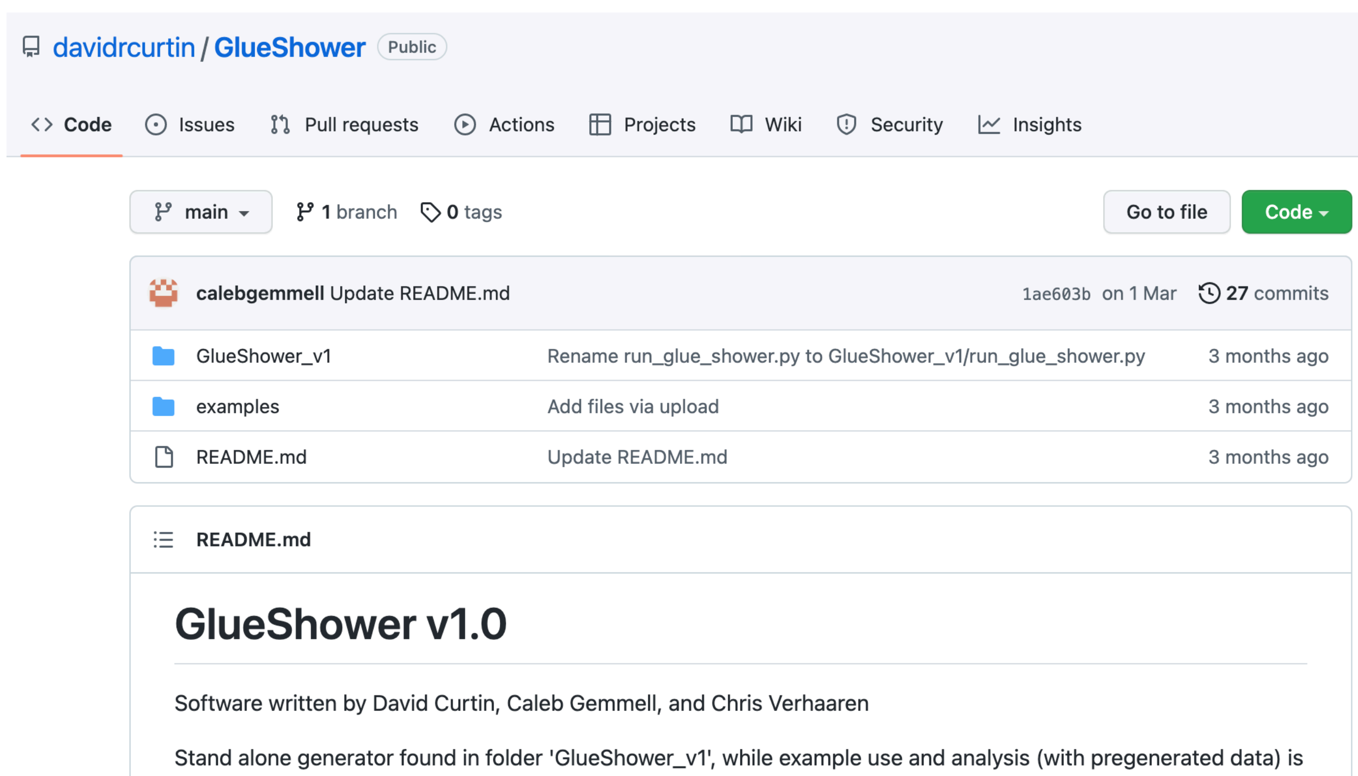
- Large 't Hooft coupling $\lambda = \alpha_D N_{c_D}$: unsuppressed large- angle radiation → wide, spherical showers; small class of theories have been proven to exist
- No dedicated simulation tools, at best some idealised approximations exist
- Common underlying feature is global radiation pattern, event shape observables can serve as useful analysis tool
- New variables to quantify event isotropy for SUEP benchmark models
- Experimental avenues being investigated; care in handling tools necessary
- Trigger strategies create bias towards less spherical events



Beyond QCD-like theories: Glueballs

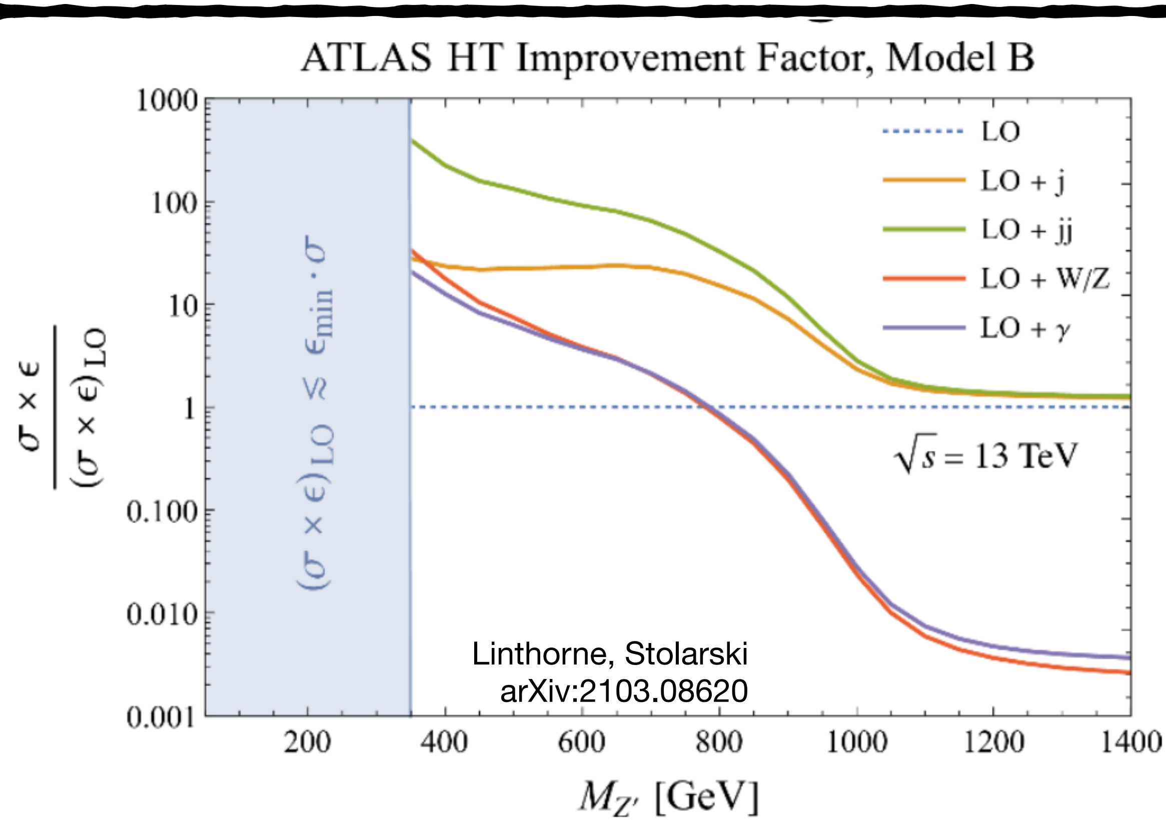
Curtin, Gemmell, Verhaaren
arXiv:2202.12899

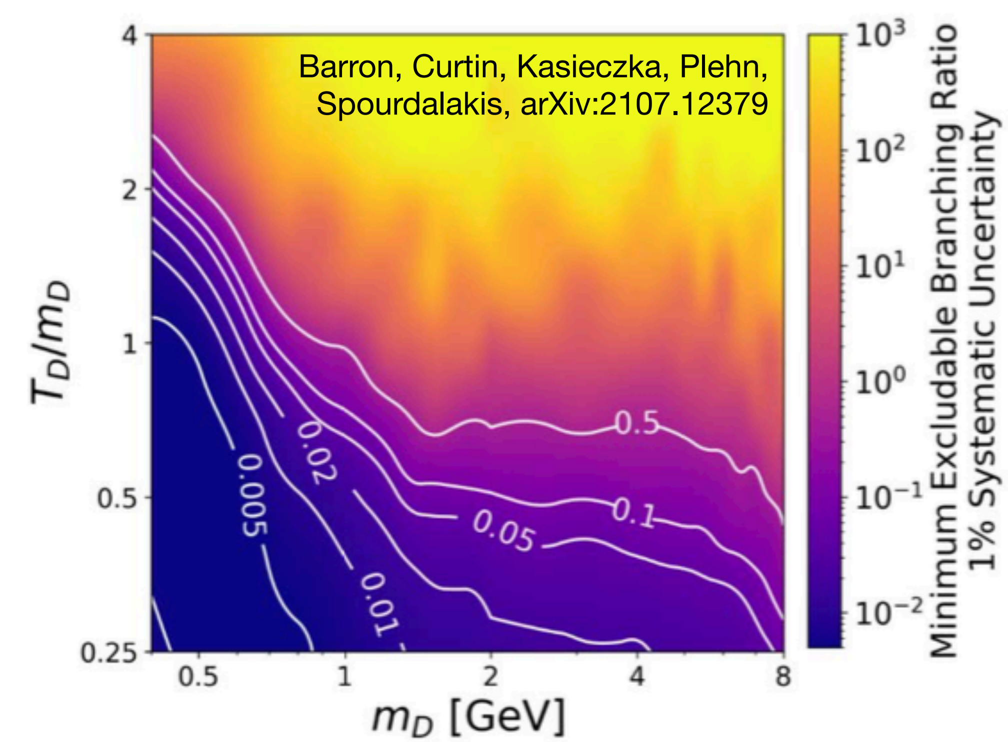
- Occur in simplest non-Abelian theories, theories containing no light fermions or scalars
- These refer to bound states of gluons, theories characterised entirely by confinement scale; spectrum computed on lattice
- First effort for creating Yang-Mills parton shower and hadronization
- First publicly available simulation tool with two different hadronization settings
  - Perturbatively motivated jet-like hadronization
  - More exotic SUEP like final state



Improved strategies

- Dark jets/SUEPs 'look' different than the SM jets, quantifying these differences lead to improved analysis strategies
- Major pathways: define new discriminating variables, define new triggers, use supervised machine learning or even auto encoders
- For e.g.
  - Alternative triggering from ISR can bring in improvement in HT and MET triggers for low Z'
  - Training on particle distance matrix of QCD background can exclude Higgs to SUEP BR to 1% for a range of signal model parameters





Future plans

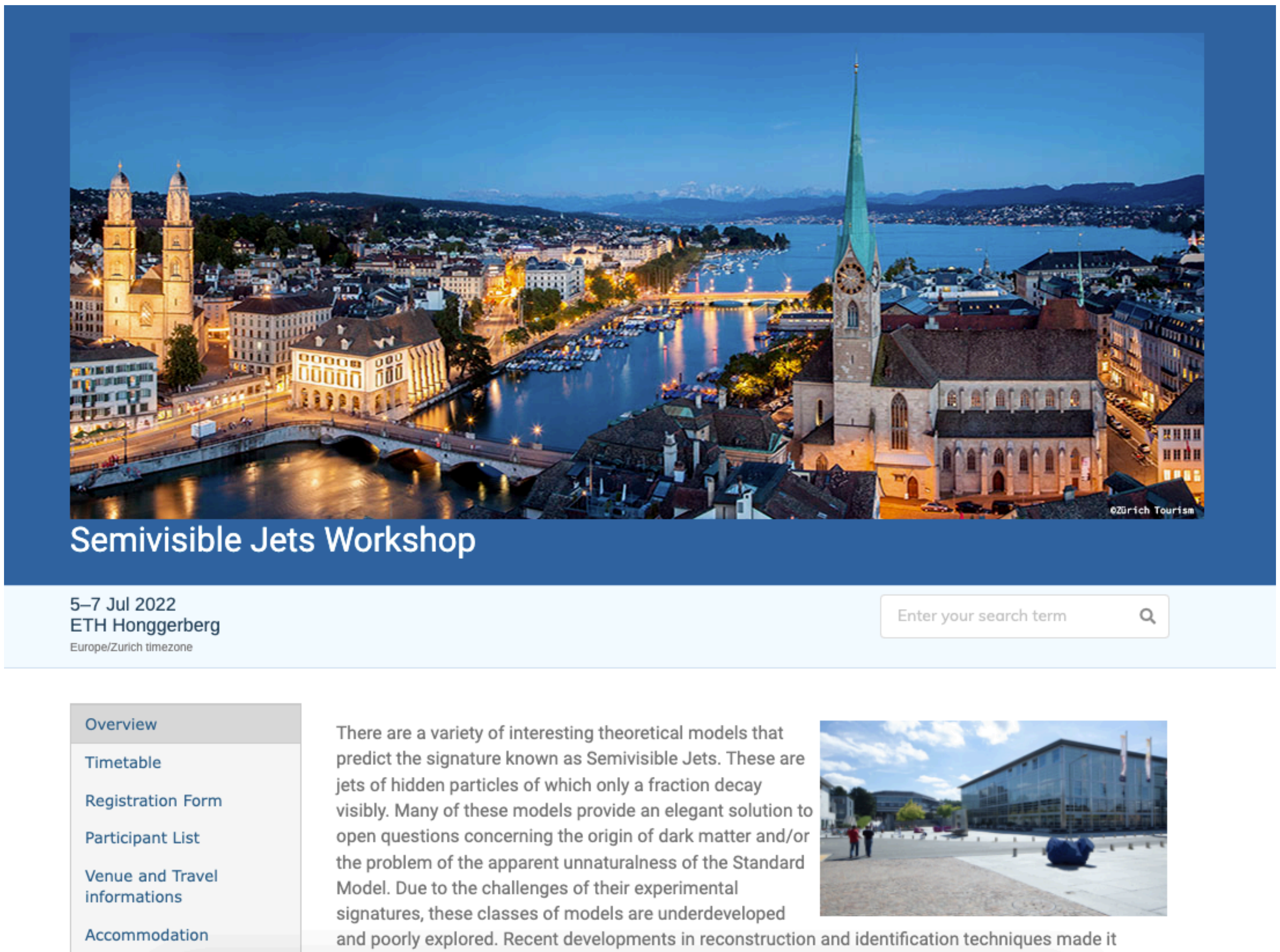
- Snowmass darkshowers white paper v2 in progress
- Fully understand the consequences of new theory understanding including mass spectrum and decay modes, include singlets consistently
- Understand the overlap between 'first principles' models and simplified models approach
- Validate and understand PYTHIA8$_{(8.307)}$ HV hadronization module
- Understand the impact on jets including substructure variables, check impact of substructure variables IRC safety or non-safety on search strategies
- Explore effects in heavy flavour and LLP final states
- Take advantage of new PYTHIA8$_{(8.307)}$ HV module to simulate a range of strongly interacting theories
- Cross correlate with dark matter analyses
- Explore Machine learning techniques

(Totally unbiased advertisement)

Upcoming: workshop on semivisible jets in Zurich 5 - 7 July

Indico site: here

Feel free to contact organisers in case of questions



Local Organization Committee

- Annapaola de Cosa (ETH Zurich)
- Jeremi Niedziela (ETH Zurich)
- Cesare Cazzaniga (ETH Zurich)
- Florian Eble (ETH Zurich)

International Scientific Committee

- Marcella Bona (Queen Mary University)
- Timothy Cohen (University of Oregon)
- Annapaola de Cosa (ETH Zurich)
- Suchita Kulkarni (University of Graz)
- Matthew Strassler (Harvard University)

Conclusions

- Strongly interacting dark sectors can explain a variety of SM shortcomings and present interesting opportunities at the experiments
- A strong phenomenological and experimental program exists
- 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 first 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 →Λ_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

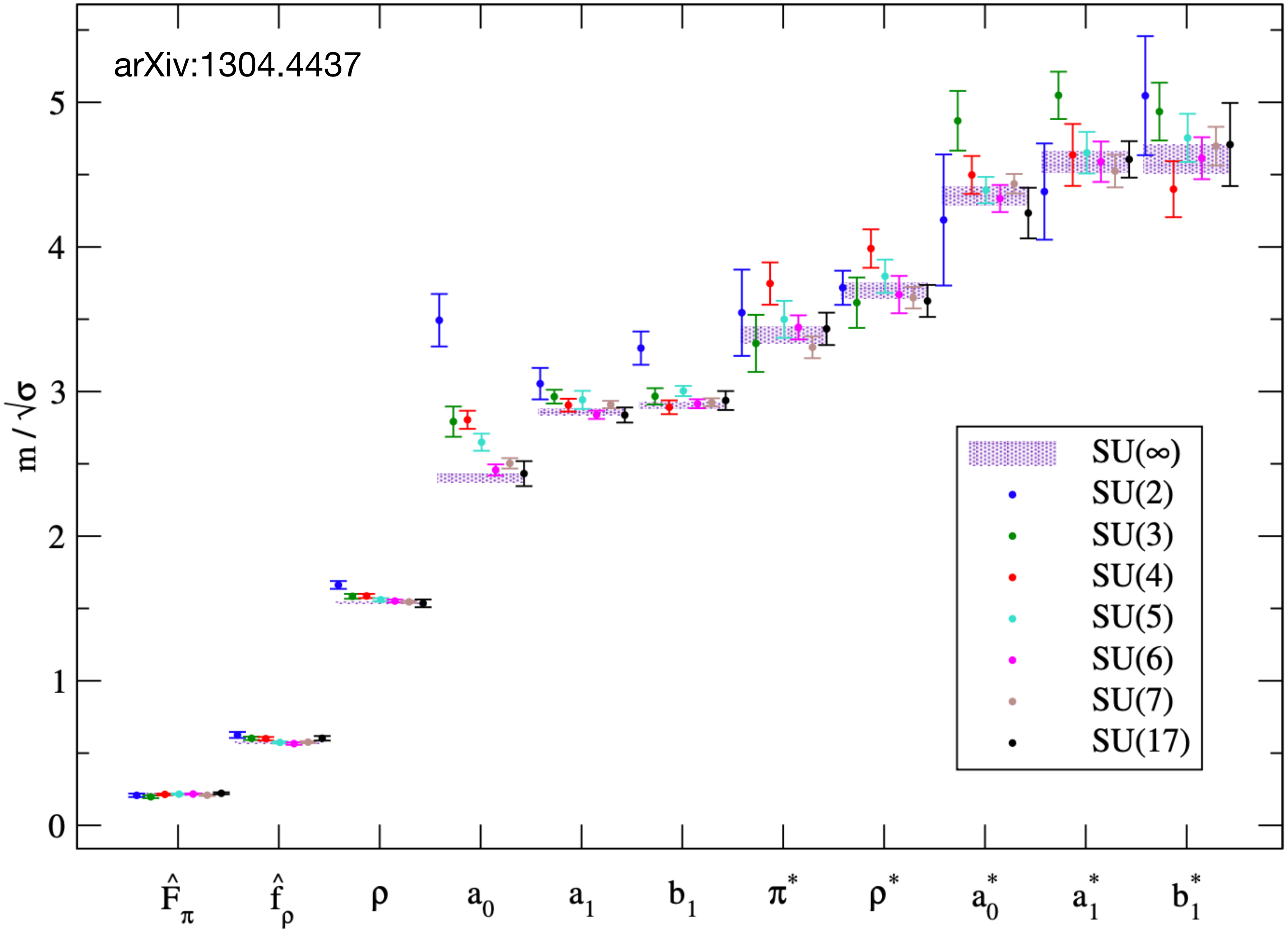
- For a theory with N_f flavours, number of pions are $N_f^2 - 1$
- Mass degenerate quarks imply mass degenerate pions (and rho)
- Out of these $N_f - 1$ are diagonal pions and $N_f(N_f - 1)/2$ off-diagonal pions
- Pythia models these diagonal and off-diagonal states using three pions, pythia assigns 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 x number of diagonal pions decay then the rescale factor is $x/(N_f - 1)$
- Similarly for y number of off-diagonal pions decaying the probability is $y/(N_f(N_f - 1)/2)$

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

- Theory dictates that equal number of diagonal and off-diagonal pions and rhos decay in any given theory (if rho to pi threshold is closed)

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

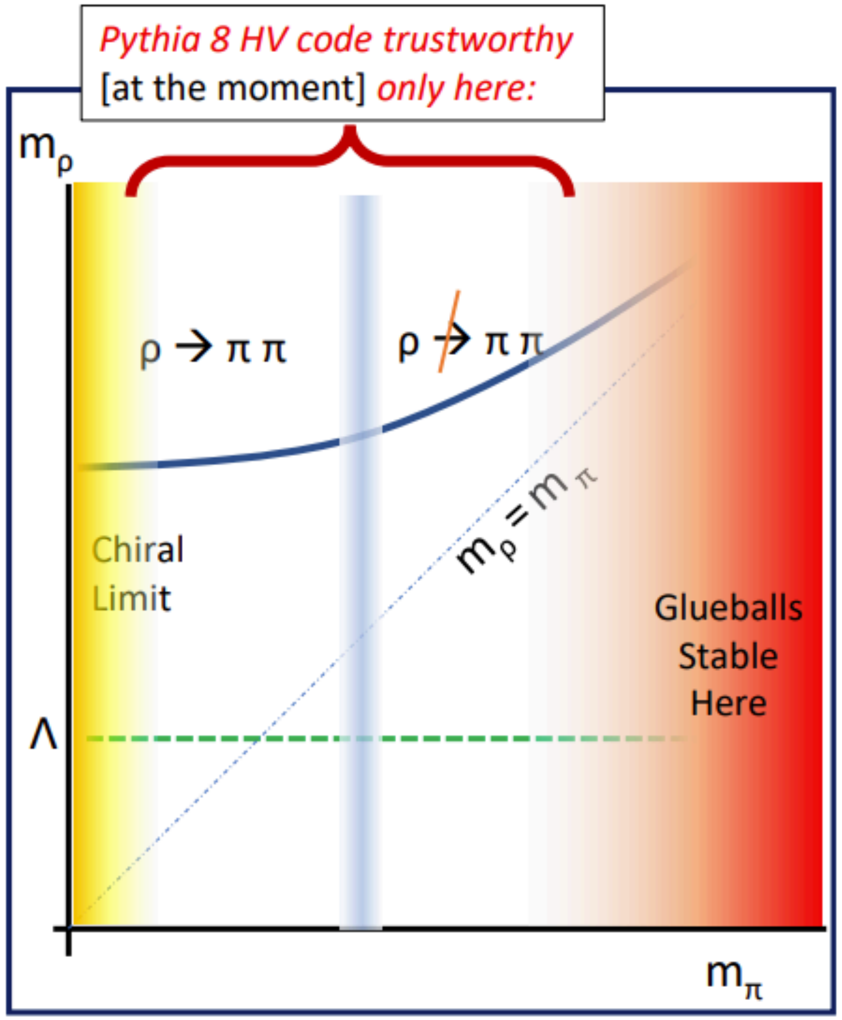


Fig. M. Strassler

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, N_f	Λ_v [GeV]	**Q**	m_{π_v} [GeV]	m_{ρ_v} [GeV]	Stable dark hadrons	Dark hadron decays
$m_{\pi_v} > m_{\rho_v}/2$	3,4	10	(-1,2,3,-4)	17	31.77	All π_v	$\rho_v^0 \to q\bar{q}$ $\rho_v^\pm \to \pi_v^\pm q\bar{q}$
$m_{\pi_v} < m_{\rho_v}/2$	3,3	5	Various	3	12.55	$0/1/2\pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$
	3,3	10	Various	6	26	$0/1/2\ \pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$
	3,3	50	Various	30	125.5	$0/1/2\ \pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$