this is what happen when one is tired and tries to find scientific illustrations in the laziest possible way @suchi_kulkarni
Darkshowers a.k.a semivisible jets – Theory perspective

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Based on Snowmass darkshowers  arXiv:2203.09503
What we have in mind

• Only thinking about new $SU(N_c)$ gauge group uncharged under the SM with s-channel
  DS - SM mediators

$\Rightarrow$ Darkshowers

$\Rightarrow$ Darkshowers

DS
Contains a confining non-Abelian group with scale $\Lambda_D$

External mediator: feeble
interactions with SM, scale $m_{med}$

SM

See S. Sinha’s talk for experimental aspects

• Jets with large MET inside
• Jets with displaced vertices
• Jets with too many or too few tracks

Semi-visible jets correspond to jets with large MET without displaced vertices
(Side remark SM mediators)

If dark sector if charged under the Standard Model, there are typically no jets

\[ \eta = \frac{m_{\pi D}}{m_{\rho D}} \]

See talk by E. Raynolds for new ATLAS results
(Side remark SM mediators)

If dark sector if charged under the Standard Model, there are typically no jets

Direct detection constrains DM - SM coupling

\[ \eta = \frac{m_{\pi D}}{m_{\rho D}} \]

η = 0.55
η = 0.70
η = 0.77
η = 1

See talk by E. Raynolds for new ATLAS results
If dark sector if charged under the Standard Model, there are typically no jets
What we have in mind

Twin Higgs see e.g. Chako, Goh, Harnik hep-ph/0506256
Why strongly interacting theories

- Composite Higgs: dark sector (DS) scale related to SM
- This talk: no relation between DS and SM scales

**New class of signatures**

Strassler et al hep-ph/0604261
Cohen et al arXiv:1503.00009
Schwaller et al arXiv:1502.05409
LLP community report arXiv:1903.04497
Kahlhoefer et al arXiv:1907.04346
Hofman et al arXiv:0803.1467
Strassler arXiv:0801.0629
Knapen et al arXiv:1612.00850

**New dark matter candidates**

Hochberg et al arXiv:1512.07917
Kribs et al arXiv:1604.04627
Cline et al arXiv:2108.10314
Berlin et al arXiv:1801.05805
Fransden et al arXiv:1103.4350
Soni et al arXiv:1602.00714, 1610.06931, 1704.02347

Talks by G. Durieux, J.M. Lizana

Strongly interacting theories: pathways

How to make systematic progress in the landscape of darkshowers?

- Symmetries and symmetry breaking mechanisms
- Lattice simulations
- Chiral perturbation theory/EFT techniques
- New cosmological analysis of DM
- New experimental signatures
- New understanding of non-perturbative dynamics?

N.B. All calculations can be done on lattice, but they are expensive, perturbative analysis is pragmatic way out
**Dark sector: composition**

### UV physics contains
- Gauge fields (gluons)
- Matter fields i.e. Dirac/Majorana fermions, Scalars (in representation \( N_r \))
- This talk: **mass degenerate Dirac fermions in fundamental representation of** \( SU(N_{C_D}) \) (event generators limitation)

### In IR

- Two discrete parameters \( N_{c_D}, N_{f_D} \)
- Two continuous parameters \( m_{q_D}, \alpha_D(\mu) \) (UV)
  - \( \Lambda_D, m_{\pi_D}/\Lambda_D \) or \( m_{\pi_D}, m_{\rho_D}/m_{\pi_D} \) (IR)
- \( N_{c_D} \neq 2 \): fundamental representation in \( SU(2) \) gauge group is pseudo-real
- \( N_{f_D} \neq 1 \): 1 flavour theory has no pions
  
  Flavour, parity, CP conserving \( SU(N_{C_D}) \) theories
Non-$SU(N_{CD})$ gauge groups

- Number of pions and rho mesons in 2 flavour theories
  - Complex: $N_{\pi_D} = 3, N_{\rho_D} = 3$
  - Pseudo-real: $N_{\pi_D} = 5, N_{\rho_D} = 10$
  - Real: $N_{\pi_D} = 9, N_{\rho_D} = 6$
- Colour flows are different for pseudo-real and real gauge groups; not encoded in current event generators

S.K., J. Pomper (in preparation)
See also Hochberg et al arXiv:1512.07917
SU($N_{CD}$) collider signatures

- Few different regimes in signature space

  - Theories make (dark) jets (QCD-like theories)
    - $\alpha_D N_{CD}$ small
  - Theories don’t make (dark) jets
    - They make Soft Unclustered Energy Patterns (SUEPs)
    - $\alpha_D N_{CD}$ large

- Event shapes in between

In this talk
- Can simulate with PYTHIA8

Not in this talk
- Out of scope of current event generators
- Few special tools exist

S. Kulkarni

26 May 2023
QCD-like theories

- For mass degenerate fermions theory has four free parameters $N_{c_D}, N_{f_D}, m_{\pi_D}/\Lambda_D, \Lambda_D$

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

- QCD-like theories: asymptotically free theories and are in chirally broken phase
Mass spectrum

- SU($N_{c_D}$), $N_{c_D} > 2$ 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 (just like the SM case)

$$\Pi^{SM} = \left( \begin{array}{ccc} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & K^0 & -\sqrt{\frac{2}{3}}\eta \end{array} \right) + \eta' \quad \rho^{\mu,SM} = \left( \begin{array}{ccc} \frac{\rho^0_\mu}{\sqrt{2}} + \frac{\omega_\mu}{\sqrt{6}} & \rho^+_\mu & K^{*+}_\mu \\ \rho^-_\mu & -\frac{\rho^0_\mu}{\sqrt{2}} + \frac{\omega_\mu}{\sqrt{6}} & K^{*-}_\mu \\ K^*_\mu & K^{*0}_\mu & -\sqrt{\frac{2}{3}}\omega_\mu \end{array} \right) + \phi$$

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

$$\frac{m_{\pi_D}}{\Lambda_D} = 5.5 \sqrt{\frac{m_{q_D}}{\Lambda_D}}$$

$$\frac{m_{\rho_D}}{\Lambda_D} = \sqrt{5.76 + 1.5 \frac{m_{\pi_D}^2}{\Lambda_D^2}}$$

π must decay for visible darkshowers

BR($\rho_D \rightarrow \pi_D\pi_D) \approx 1$
Flavour symmetry breaking leads to (dark)showers

\[ SU(N_{C_D}) \text{ Fund. rep., } SU(N_{F_D}) = 2, \]

\[ Q_D = \text{Diag}(+1, -1) \]

- **Example 1:** \( N_{f_D} = 2; n_{\pi_D} = n_{\rho_D} = 3; Q_D = \text{Diag}(+1, -1); \)
  - Doublet \((\pi_D^{++}, \pi_D^{--}); (\rho_D^{++}, \rho_D^{--})\)
  - Singlets \((\pi_D^0); (\rho_D^0)\)
  - \(\rho_D^0 - Z'\) mixing leads to visible decays
  
  *For charges of type Diag(+1... -1) only one diagonal \(\rho_D^0\) mixes with \(Z'\)*

- **Example 2:** \( N_{f_D} = 4; n_{\pi_D} = n_{\rho_D} = 15; Q_D = \text{Diag}(-1, +1, -2, +2); \)
  - All diagonal \(\rho_D^0\) mix with \(Z'\)
Dark rho meson decays

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

Regime 1
\[ \rho_D \rightarrow \pi_D \pi_D \]

Regime 2
\[ \rho_D \rightarrow \pi_D \pi_D \]

Regime 2
\[ \rho_D \rightarrow \pi_D \pi_D \]

- Regime 2, \( m_{\rho_D} < 2 m_{\pi_D} \):
  - \( \Gamma(\rho_D \rightarrow \pi_D f \bar{f}) \propto \frac{m_{\rho_D}^{11}}{\Lambda_D^6 m_{Z'}^4} \Rightarrow \text{Potential LLPs!} \)
  - Not captured in previous LHC phenomenology

- Example 1: \( N_{f_D} = 1 \) both off-diagonal \( \rho_D \) decay via three body
  - Example 2: \( N_{f_D} = 4 \) seven \( \rho_D \) decay via three body
Dark pion decays

UV theories

IR portals

LHC signatures

SVJ composition depends on $Z'$ properties

SVJ typically rich in HF

See Strassler, Zurek hep-ph/0604261
Choosing $m_{Z'}$

- For $m_{Z'} \gg \Lambda_D$ hard production is followed by dark parton shower and hadronization, for $m_{Z'} \sim \Lambda_D$ dark shower and hadronization shuts down $\rightarrow$ dark hadron production
- First approximate quantitative study to establish these regimes $\rightarrow$ pick $m_{Z'} \gtrsim 30\Lambda_D$
Impact on SM final states

- Number of decaying pions can lead to differences in jet substructure variables
- Some of the jet substructure variables (e.g. $p_T^D$) are not IRC safe, care should be taken while using them
- Regime - II scenarios, not yet explored
- (Dark) Hadronization uncertainties can be significant, did not explore in details
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

• A successful exploration of strongly interacting sectors benefits from understanding the theories in UV and IR and is further complemented by lattice simulations
  • Defined theoretically consistent darkshowers scenarios for dark quark mass degenerate regime
  • Identified less explored spin-1 meson decays
  • Demonstrated need to carefully study IRC safety of jet substructure variables
  • Performed first validation of PYTHIA8 for simulating darkshowers (not presented in the talk)

• Did not consider mass split scenarios
  • More theory work necessary
  • PYTHIA8 validation necessary

• More SM - DS portals can be constructed and can lead to more exotic dark showers

• If you want to design a search for darkshowers talk to (more than one) theory friends before choosing your favourite model
Backup
How to get jets?

- Choose $N_{cD} > 2$ and $N_{fD} > 1$, $\Lambda_D > 1 \text{GeV}$, stay within asymptotically free region
- Pick $0.25 < m_{\pi_D}/\Lambda_D < 2$ and set mass spectrum
- 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 $m_{q_{\text{const}}} \equiv m_{q_D} + \Lambda_D$ (this is not an exact relation)
- Pick $m_{Z'} \gtrsim 30\Lambda_D$ to get jets
- Neglect special treatment for singlets for now
- Assume baryons are heavy thus irrelevant
- Depending on $m_{\pi_D}/\Lambda_D$ and portal, set the dark meson decay modes
- Note: $m_{\pi_D}/\Lambda_D < 1.53 \Rightarrow \rho_D \rightarrow \pi_D \pi_D$ open!
Beyond QCD-like theories: SUEP

- Large 't Hooft coupling $\lambda = \alpha_D N_{cp}$: unsuppressed large-angle radiation $\rightarrow$ 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

![Graphs showing event shape observables](https://example.com/graphs.png)
Beyond QCD-like theories: Glueballs

- 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

\[ \Lambda_{had}/2m_0 = 1 \]

Jet like shower

\[ \Lambda_{had}/2m_0 = 4 \]

Plasma like shower

Lightest glue ball mass = \( m_0 \)
PYTHIA8 improvements and validation

- 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?

- 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
‘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 $y/(N_f(N_f - 1)/2)$

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

- 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)
• 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

arXiv:1304.4437
Benchmarks

- A few suggested first list of benchmarks in Snowmass
- Applicable for s-channel vector mediated SM - DS interactions

<table>
<thead>
<tr>
<th>Regime</th>
<th>$N_{c_D}, N_{f_D}$</th>
<th>$\Lambda_D$ [GeV]</th>
<th>$Q$</th>
<th>$m_{\pi_D}$ [GeV]</th>
<th>$m_{\rho_D}$ [GeV]</th>
<th>Stable dark hadrons</th>
<th>Dark hadron decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\pi_D} &lt; m_{\rho_D}/2$</td>
<td>3,3</td>
<td>5</td>
<td>Various</td>
<td>3</td>
<td>12.55</td>
<td>0/1/2$\pi_D^0$</td>
<td>$\rho_D^{0/\pm} \rightarrow \pi_D^{0/\pm} \pi_D^{\mp}$ $\pi_D^0 \rightarrow c\bar{c}$</td>
</tr>
<tr>
<td></td>
<td>3,3</td>
<td>10</td>
<td>Various</td>
<td>6</td>
<td>25</td>
<td>0/1/2$\pi_D^0$</td>
<td>$\rho_D^{0/\pm} \rightarrow \pi_D^{0/\pm} \pi_D^{\mp}$ $\pi_D^0 \rightarrow c\bar{c}$</td>
</tr>
<tr>
<td></td>
<td>3,3</td>
<td>50</td>
<td>Various</td>
<td>30</td>
<td>125.5</td>
<td>0/1/2$\pi_D^0$</td>
<td>$\rho_D^{0/\pm} \rightarrow \pi_D^{0/\pm} \pi_D^{\mp}$ $\pi_D^0 \rightarrow b\bar{b}$</td>
</tr>
<tr>
<td>$m_{\pi_D} &gt; m_{\rho_D}/2$</td>
<td>3,4</td>
<td>10</td>
<td>(-1,2,3,-4)</td>
<td>17</td>
<td>31.77</td>
<td>All $\pi_D$</td>
<td>$\rho_D^{0/\pm} \rightarrow q\bar{q}$ $\rho_D^{\pm} \rightarrow \pi_D^{\pm} q\bar{q}$</td>
</tr>
</tbody>
</table>
Running of $\alpha_D$

- Running depends on $N_{f_D}/N_{c_D}$
- Two loop corrections become important as $N_{f_D}/N_{c_D}$ increases
Primary obstacles in getting DM candidate

- DM longevity needs to be ensured
- Impose external symmetries
- Use accidental symmetries e.g. lightest baryon (proton) is stable in the SM due to baryon number conservation
- Engineer models to ensure stability

\[ S U(N_{C_D}) \text{ rep.}, S U(N_{F_D}) = 2, \]

\[ Q_D = \text{Diag}(+1, -1) \]

Coupling with \( Z' \)

\[ q_D(u, d)_D, \pi_D, \pi_D \]

\[ \pi_D^+, \pi_D^- \]

\[ \pi_D^0 \]

\[ \sim \text{Tr}[Q_D^2 T_0] = 0 \]

\[ \rightarrow Q_D^2 \propto 1 \]

- Quantitative estimates from genuine non-perturbative physics are needed
New avenues

- Relic density

\[ n_{\pi_D}(s)_{3\to2} \sim H \Rightarrow \frac{m_{\pi_D}}{f_{\pi_D}} \propto m_{\pi_D}^{3/10} \]

- Self-scattering

\[ \frac{\sigma_{\pi_D\pi_D\to\pi_D\pi_D}}{m_{\pi_D}} \propto \left( \frac{m_{\pi_D}}{f_{\pi_D}} \right)^4 \times \frac{1}{m_{\pi_D}^3} \]

Thermal Dark Matter, \( \Omega_{\pi} = \Omega_{DM} \)
SIMP future prospects

Hochberg et al arXiv:1512.07917

\[ SU(2), N_f = 2 \]
\[ \alpha_D = 1/4\pi \]
\[ m_\pi = 300 \text{ MeV} \]