Date: 27 May 2021

Questions about darkshower tutorial:

For questions not raised in the discussion, could you please also leave your name?

How realistic is the phenomenological consequence of setting N_C,dark and N_f,dark?
-- Simon K. : PDG codes are flavour dependent; max value should be less than 4900010 so at most 10 flavours possible. There is a single "universal" dark quark with code 4900101
-- Doesn't the sign of the 1-loop beta function determine if the dark sector is confining or not? So couldn't arbitrary choices of N_C and N_f lead to a non-confining dark sector? -- Torbjörn: Yes, only restrict to parameters that give a confining beta function. Recall that the relevant number is 11 * N_C - 2 * n_f for SU(N_C) with n_f fermions in the fundamental representation, forgetting mass effects.

What is the maximum allowed mass of the dark quark? -- currently m_pion/2

Andrii U. :Can you make rho lighter than pion -- Daniel S. : in simulation yes, but not realistic

What is a good choice for the pTminFSR model wrt to Lambda?
Torbjörn: the mentioned choice of 1.1 * Lambda was intended as the LOWEST possible choice, and if you go by our QCD experience then 2 * Lambda may be more sensible. At the same time the virtue of the string is that low emissions only give small dents, so there is some sense of infrared stability, which is why using the lowest value is still OK. This breaks down once you allow gv -> qv + qvbar, because this "chops up" the string into smaller pieces. One other reason why it has not been a big priority.

What about a dark scalar glueball (gD+gD) and if it could be lighter than 2 x dark meson could be DM or LLP?
Is it included somehow?
Torbjörn: there is a code reserved for it, and it can already now be used as a way to bookkeep small amounts of energy not easily put anywhere else. But you can start to define decay channels into our out of it, as long as you know what you want.

Mike A.: Can you have hidden glueball that is lighter than mesons and therefore is stable/LLP?
Daniel S.: Yes, theoretically possible
Torbjörn: Yes, there is an implementation in Pythia but need to check
Matt S. : You can't simulate production reliably (raising quark masses makes glueballs dominant).
Mike A.: What would be the decay mode -> Get in touch with Matt S. for more details.

S. Knapen: When one wants to eg. do jet substructure analysis, it can be useful to set alphaOrder=0 as check that the analysis is not overly model dependent.
D. Stolarski: Yes in that case it makes more sense to set this to a fixed value

K. Pedro: setting Lambda should be done carefully because otherwise the behaviour wrt mass changes can be misleading.

Question about hadron masses (does someone remember exact question?)
Torbjörn: If you are in a situation where hadrons are much heavier than lambdaQCD scale you can not extract from QCD behaviour. Current implementation okay till maybe strange/charm is lightest but otherwise unreliable.

Lattice paper mentioned by Simon: https://arxiv.org/abs/1910.08561

Pythia Hidden valley documentation:

Pythia and Docker commands:

```
docker pull mgenest/dark-shower-tutorial

docker run -it mgenest/dark-shower-tutorial sh

cd pythia8245/examples

make maindark

./maindark darkshower_semi_visible.cmnd

python3.8 ZprimeMass.py
```

Now you should have a PDF histogram file

Copying the pdf files to your local machine

```
docker ps --format "{{.Names}}"

docker cp <container name>:pythia8245/examples/mZp.pdf <local path>
```

Andreii: Why is there a low-mass tail? Torbjörn: PDFs grow faster at low mass than fall-off of the Breit-Wigner. BW description is only valid near peak.

SUEPs

Karri's talk summarised: Two Pythia instances. First produces a higgs. In the second instance, manually add multiple new scalars generated using Boltzmann distribution, boosted to lab-frame (using higgs mass and momentum). Scalars then decayed exclusively to dark photons (added by hand as a new particle) which then decay to light leptons. Result is LOTS of low-pT tracks.

Suchita: What are sensible parameters in the dark sector?
Simon: High temperature (T~m_phi) results in few particles carrying most of the momentum, no longer statistically accurate. Restrict to high mH/T to retain qualitative description, with mH the heavy mediator
Matt: For a heavy mediator produced at 100 TeV collider, you could certainly also do m_phi ~ 50 GeV without problems.

Discussion session: simulating dark showers with pythia hidden valley module

Moderator: Marat Freytsis
On panel: Daniel Stolarski, Simon Knapen, Karri Folan DiPetrillo, Matt Strassler, Torbjörn Sjöstrand

Splitting of dark gluon to dark quarks:
T.S.: Easily done if needed

More complicated hadronisation spectrum
J.S. Pythia doesn't like light dark quarks
T.S. Up to 8 flavours should be no problem, that gives you 64 scalar and 64 vector mesons.
M.S The main problem is we don't fully know how to calculate all the decay modes, which could have phenomenological consequences. Putting it into Pythia's decay table is the easy part.
[Question by Suchita: Trivial question, how does one get 'access' to these 64 scalars and 64 mesons? Can I e.g. change their masses, decay patterns?]
Yes, the same way you set pion mass e.g. 4900211:m0 = …
[Suchita: okay but then these potentially correspond to different underlying quark masses, exactly like in SM, so I need copies of quarks too? I am particularly thinking of dark quarks which are NOT charged under the SM]
There are already multiple dark quarks available in the module 4900001 - 4900008.
[Suchita: Wait these are charged under both SM and HV right? "A minimal HV particle content has been introduced. Firstly, there is a set of 12 particles that mirrors the Standard Model flavour structure, and is charged under both the SM and the HV symmetry groups" from the pythia HV webpage]

Torbjörn: In the code, consider FlavContainer HVStringFlav::pick and HVStringFlav::combine In HiddenValleyFragmentation.cc. You see how currently a varying number of flavours are allowed, but then you reduce it to on-diagonal and off-diagonal. For a complete spectrum you would have to keep the idPos and idNeg and work them into the final code.
[Suchita: Thanks, this makes sense , and goes in the direction of what Matt was suggesting as well! I thought there are already 64 mesons available when DS is not charged under SM via the simplistic interface we were working with. I understand that modifications will generate what one would be interested in going in this direction. :)]

M.S. Can the workshop group do a realistic calculation with three non-degenerate quark masses, looking at decay chains and lifetimes as a function of the quark masses? Requires careful use of chiral Lagrangian techniques.
Suchita.K: Further complications from adding mediators. Can we learn from what we know from lattice/QCD? In which scenarios is Pythia reliable -- degenerate quarks with QCD-like HV only or other regimes as well?

J.S. Lattice shows rich decay patterns, already difficult to implement in Pythia because you need non-string-model hadronisation. You cannot decouple uncertainties from observables (multiplicities of specific hadron species are not IR safe quantities). Use Pythia to cover signature space rather than focussing on getting the hadronic spectrum exactly right.

M.S. When you go beyond data, theorists don't know how to calculate. Hadronisation is a real time process and cannot be done with lattice. Strong dark coupling [large g^2 Nc] would also make perturbative showering calculations inaccurate. If you push to optimise sensitivity to a particular peccadillo of a theory, you risk losing sensitivity to many other possibilities; need to find a balance.

Simon.K.: We can maximise the phenomenology that can be covered by current Pythia implementation.

M.F. If we want to make sure to not miss anything, perturbation on QCD-like modules is not what we should be focussed on, but have some very non-QCD model that can be implemented in a independent model.

M.S. A new implementation we could put into Pythia's HV is a model https://arxiv.org/abs/2009.08981 [work with Cesarotti and Reece] that interpolates between jetty and SUEP-like events. It's not coupled to SM yet. It could be and then this would be an example of Marat's non-QCD idea.

M.S. E.g. theory is higgsed and you mainly have dark gluons. This was studied in 2008-9 by Meade, Papucci and Volansky https://arxiv.org/pdf/0901.2925.pdf . Experimentalists have not studied this theory yet.

T.S. This example could be put into Pythia.

C.C : Our toy model captures the idea of focussing on signature space.

M.S. The model C.C. refers to uses the idea that in strongly coupled theories [large g^2N], you have a tower of (stable) hadrons which can go into SM hadrons. If the SM produces a state high in the tower, its decay chain is calculable (using extra dimensional methods) and can give a variety of final states, which can be SUEPy or jetty depending on parameters.

J.S. Can we generate non-QCD like energy distributions as a stress test of experimental coverage? A stick figure version of this would be useful already.

Next steps for Dark Showers studies at the LHC

1. Generate non-QCD like energy distributions as a stress test of experimental coverage
   a. E.g. theory is higgsed and you mainly have dark gluons. This was studied in 2008-9 by Meade, Papucci and Volansky https://arxiv.org/pdf/0901.2925.pdf. This can be put into Pythia
   b. https://arxiv.org/abs/2009.08981, computes hadronic cascades in large-coupling models that can be jetty or SUEPy depending on parameters.

2. Use Pythia to cover signature space rather than focussing on getting the hadronic spectrum exactly right. --- How to do this needs more thought

3. Implementing a more complicated hadronisation spectrum in Pythia: start by using 3 non-degenrate quarks.

Literature shared during discussion

[1] https://arxiv.org/abs/1910.08561 : discusses lattice inputs for simulations
[2] https://arxiv.org/pdf/0901.2925.pdf, uses shower of dark gluons in a Higgsed SU(N)

[3] https://arxiv.org/abs/2009.08981 , computes hadronic cascades in large-coupling models that can be jetty or SUEPy depending on parameters.