Simulating SUEP Signatures

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9th workshop of LHC LLP community
Dark Showers Session
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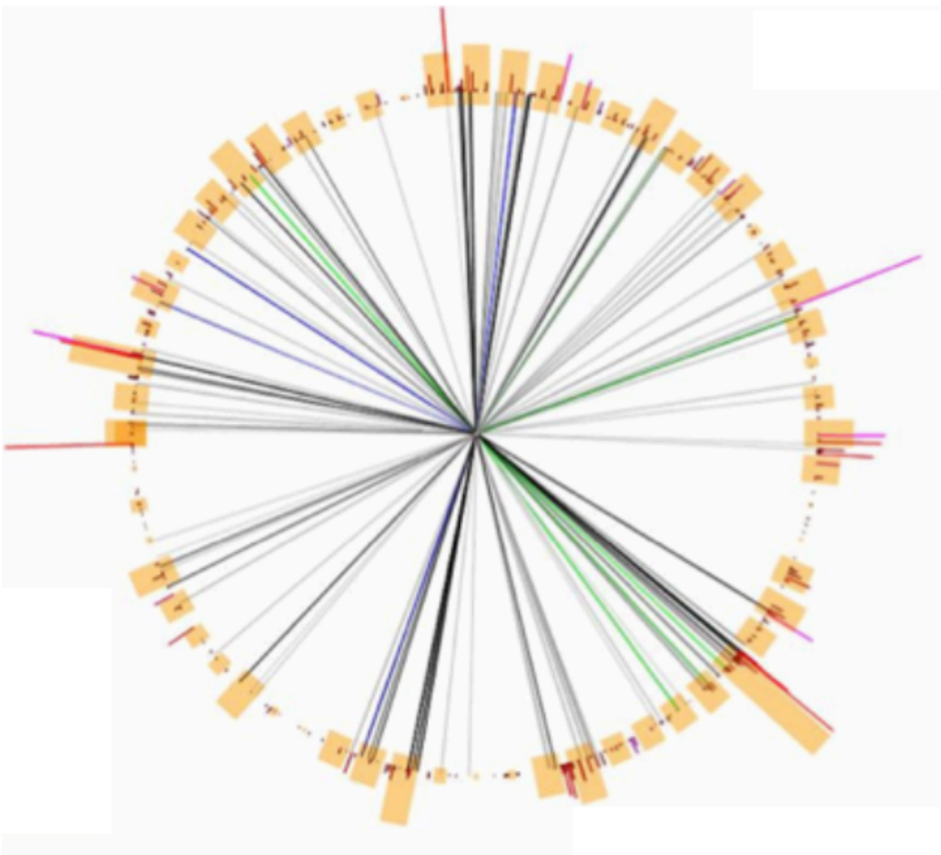
SUEPs

- SUEPs = Soft Unclustered Energy Patterns
  - also known as soft-bombs or fireworks
  - characterized by a large number of soft charged particles and spherical event shape
- Motivated in dark QCD scenarios
  - large t'Hooft coupling, $\alpha_{dark}^2 N \gg 1$
  - In this limit dark QCD is no longer predominantly soft and co-linear, but leads to large angle, high p_T radiation
- Experimental perspective
  - challenging for LHC trigger
  - uncovered phase space



Simulating SUEPs

using Pythia8 plugin from Simon Knapen
https://gitlab.com/simonknapen/suep_generator
Triggering Soft Bombs at the LHC

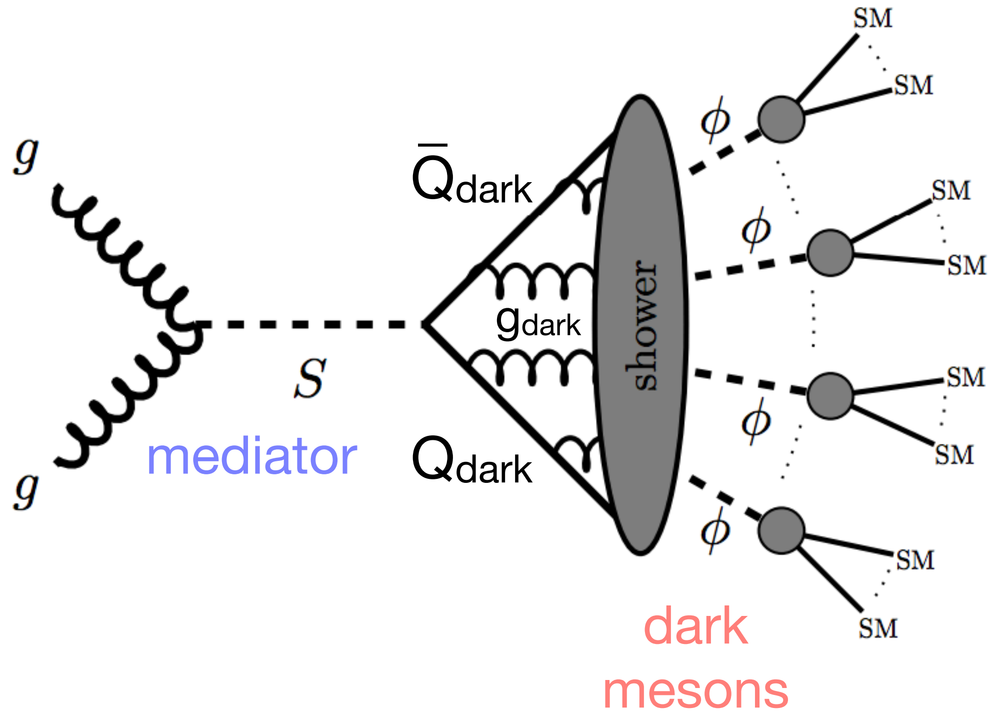
production via
scalar mediator, S

dark shower to single flavor of
light dark mesons, ϕ

dark meson p_T described by
Maxwell-Boltzmann, temperature, T

dark mesons decay back to
SM particles

Benchmark Model



*Possible to modify mediator and decay mode

Production

Production: scalar mediator via gluon gluon fusion

pdgID = 25, user specifies scalar mass

typical target: O(100) GeV < m_S < O(1) TeV

easy to modify mediator, center of mass energy, etc

suep_main.cc

```
  // We will run pythia twice: Once for Higgs production, and once to decay th
e final state mesons of softbomb.
  // We therefore need two different pythia objects, each with different setti
ngs
  Pythia pythiaProd, pythiaDecay;

  //Settings for the production Pythia object, before softbomb shower
  pythiaProd.readString("Beams:eCM = 13000.");
  pythiaProd.readString("HiggsSM:all = on");
  pythiaProd.readString("25:mayDecay = off"); // turn off SM decays for Higgs
  pythiaProd.readString("25:m0 = "+tostr(mh)); // set the mass of "Higgs" scal
ar
  pythiaProd.readString("Random:setSeed = on");
  pythiaProd.readString("Random:seed = "+seed);
  pythiaProd.readString("Next:numberShowEvent = 0");
  // For debugging only
  //pythiaProd.readString("PartonLevel:ISR = off");
  //pythiaProd.readString("PartonLevel:FSR = off");
  //pythiaProd.readString("HadronLevel:Hadronize= off");
  pythiaProd.init();
```

Dark Shower

Mediator decays via a dark shower to a large multiplicity of dark mesons

- Dark shower details
  - single flavor of final state dark mesons, ϕ, pdgID = 999999
  - dark meson momenta are drawn from a relativistic Maxwell Boltzmann distribution with temperature, T
  - SUEP shower is boosted into lab frame and attached to event
- What you can change
  - dark meson mass, m_ϕ and temp, T
  - typical target: m_ϕ ~ T ~ O(1) GeV

suep_shower.cc

```
// generate a shower event, in the rest frame of the shower
vector< vector <double> > Suep_shower::generate_shower(){

    vector<vector<double> > event;
    double sum_E = 0.0;

    // fill up event record
    while(sum_E<(this->Etot)){
        event.push_back(this->generate_fourvector());
        sum_E += (event.back()).at(0);
    }
```

```
// generate one random 4 vector from the thermal distribution
vector<double> Suep_shower::generate_fourvector(){

    vector<double> fourvec;
    double en, phi, theta, p;//kinematic variables of the 4 vector

    // first do momentum, following arxiv:1305.5226
    double U, V, X, Y, E;
    int i=0;
    while(i<100){
        U = ((double) rand() / RAND_MAX);
        V = ((double) rand() / RAND_MAX);

        if(U < q_m){
            Y=U/q_m;
            X=( 1 - Y )*( p_minus + lambda_minus )+Y*( p_plus - lambda_plus );
            if(V < f(X) / f(p_m) && X>0){
                break;
                }
            }
        else{if(U < q_m + q_plus){
            E = -log((U-q_m)/q_plus);
            X = p_plus - lambda_plus*(1-E);
            if(V<exp(E)*f(X)/f(p_m) && X>0){
                break;
                }
            }
```

Decay to Standard Model

Final state mesons decay promptly back to the standard model

handled by a second instance of pythia

branching ratios specified by user via decay cards

Example decay cards are provided for

$\phi \rightarrow$ dark photons $\rightarrow$ SM

$\phi \rightarrow$ qq-bar

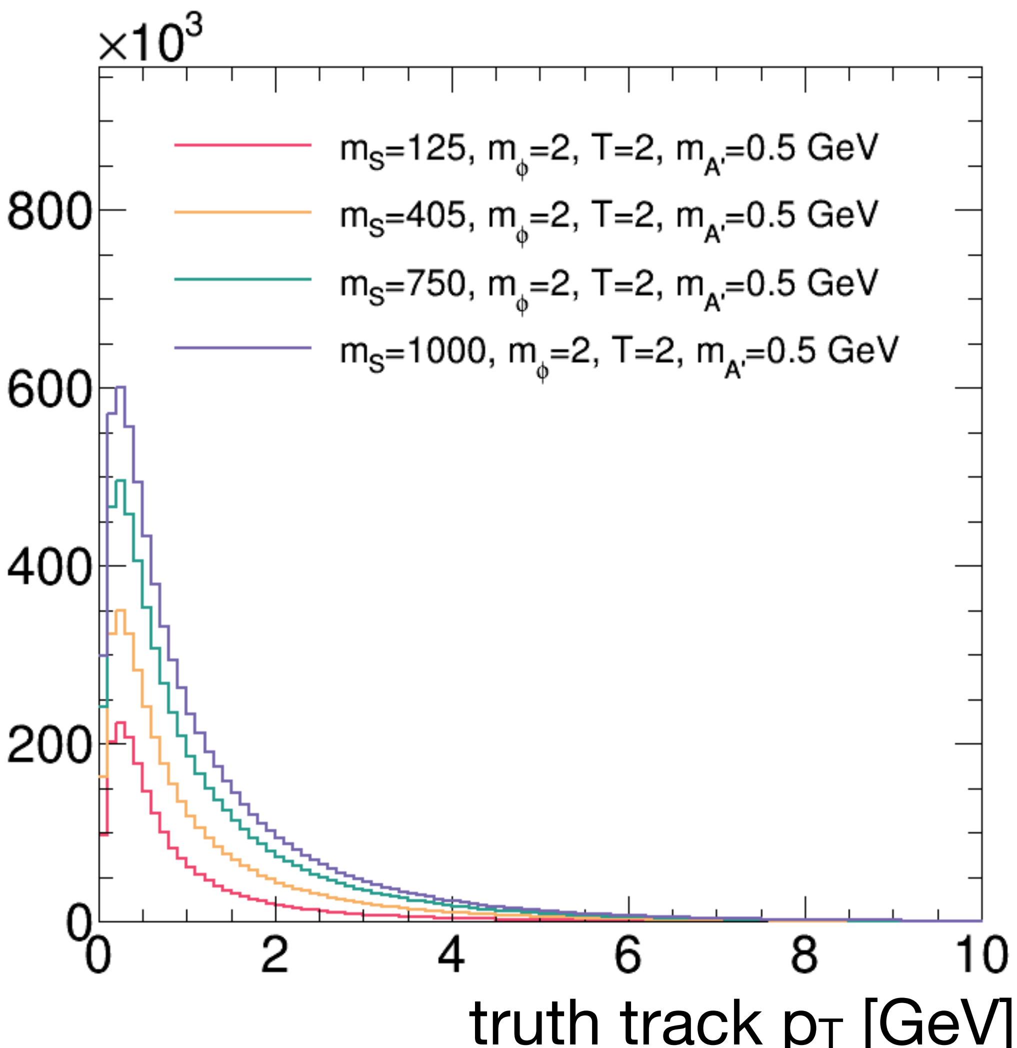
dark photon pdgID=999998

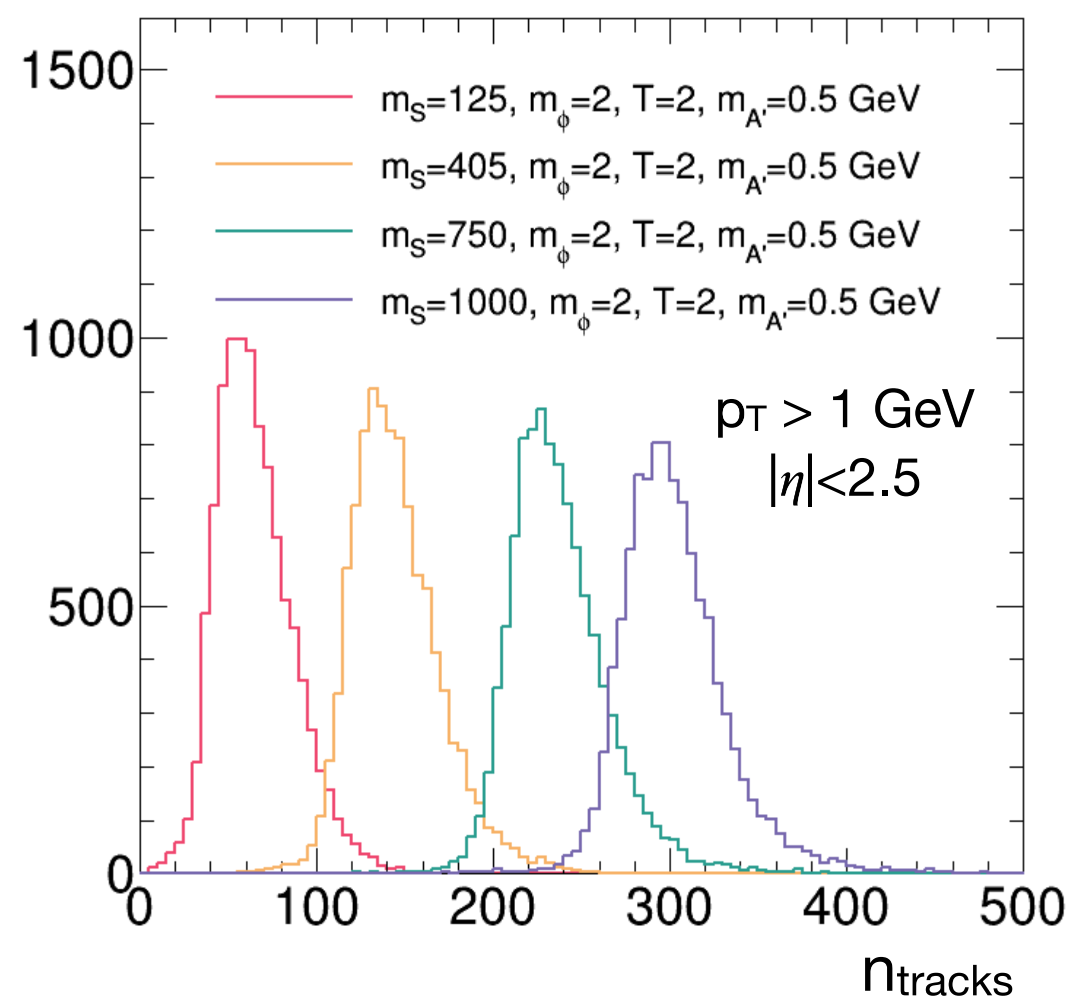
decay_cards/decay_darkphoton.cmnd

```
// This card provides the decay settings for the hidden mesons.
// See http://home.thep.lu.se/~torbjorn/pythia81html/ParticleDataSchem
e.html for syntax
// Please verify that the channels you choose are kinematically allowe
d for the meson mass you selected.
//
// In this example, we decay each dark meson two 2 dark photons (pdg c
ode 999998) which each in turn decay to SM fermions
// The dark photon branching ratios are mass dependent, see e.g. arxiv
:1505.07459. Values used here are approximate.
//
// Written by Simon Knapen on 11/02/2019

// define the dark photon with mass 0.5 GeV
999998:all = GeneralResonance void 1 0 0 0.5 0.001 0.0 0.0 0.0

// define dark meson decays
999999:addChannel = 1 1.0 101 999998 999998 // 100% branching ratio to
 pair of dark photons

// define dark photon decays
999998:addChannel = 1 0.4 101 11 -11 // 40% branching ratio to e+ e-
```

Truth Level Distributions

- Key features:
  - large multiplicity of low p_T charged particles & spherical event shape
- Varying signal parameters
  - <u>scan scalar mass:</u> n_{tracks} ~ m_S
  - scan temperature: n_{tracks} ~1/T, track p_T increases with T





*10k signal events - not scaled by XS

Tutorial Overview

- Our optimistic physics goals
  - Step 1: scan mediator mass
  - Step 2: scan temperatures
  - Step 3: vary decay modes
- How this will work operationally
  - We'll generate SUEP hepMC events in the docker container
    - or you can download output files from dropbox (~200 MB)
  - Then you can either
    - 1. make plots in the docker container & copy to your laptop
    - 2. copy hepMC to your laptop & make plots there
  - I have directions for each option, IMO option 2 is easier
- Instructions
  - Next few slides have the basic steps for getting started
  - Python notebook and basic plotting code for the rest of the tutorial: https://github.com/kdipetri/suepTutorial
    - plotting script adapted from Kate Pachal and Jess Nelson
    - event displays adapted from Christos Papageorgakis

Generating samples

```
# Make sure you have Marie Helene & Suchita's docker container setup
# Once you're in the container go into Simon's SUEP directory
cd pythia8245/SUEP
vi suep_main.cxx

# in suep_main.cxx we're going to make two changes to make our lives easier

## 1. reduce the number of events
  // number of events
  int Nevents=100;
  //int Nevents=10000;

## 2. update decay card path
  pythia.readFile("decay_cards/"+cardfilename);
  //pythia.readFile(cardfilename);

# recompile
make suep_main

# run your first sample
./suep_main 125.0 1.0 1.0  decay_example.cmnd
mMed-125_mDark-1.0_temp-1.0_decay-generic.hepmc 1
```

1. Plotting in docker

```
# in docker SUEP container
cp suep_tutorial/plot_hep_mc.py .

# In python, or create a python file test.py, and add the following lines
from plot_hep_mc import SUEP

suep = SUEP("mMed-125_mDark-1.0_temp-1.0_decay-generic.hepmc")
suep.doTest()
suep.processEvents()
suep.basicPlots(save=True)

# then try and run a test, check for image output
python3.8 test.py
ls

# In a different terminal, get container name
docker ps

Karris-MacBook-Pro:suepTutorial karridipetrillo$ docker ps
CONTAINER ID   IMAGE                                    COMMAND   CREATED
STATUS          PORTS     NAMES
0fa6d2b8da46   mgenest/dark-shower-tutorial:latest   "bash"    14 minutes
ago   Up 14 minutes             serene_gauss

# Copy file to your laptop so you can see it
docker cp serene_gauss:/pythia8245/SUEP/plotname.png .
```

2. Plotting on your laptop

```
# In a different terminal
cd ~/Documents
git clone git@github.com:kdipetri/suepTutorial.git
cd suepTutorial

# make sure you have dependencies
pip install matplotlib
pip install numpy
pip install particle
pip install pyhepmc-ng

# get container name
docker ps
```

```
Karris-MacBook-Pro:suepTutorial karridipetrillo$ docker ps
CONTAINER ID   IMAGE                                  COMMAND    CREATED          STATUS
PORTS     NAMES
0fa6d2b8da46   mgenest/dark-shower-tutorial:latest    "bash"     14 minutes ago   Up 14
minutes             serene_gauss
```

```
# If you want to copy hepMC from docker container
docker cp serene_gauss:/pythia8245/SUEP/mMed-125_mDark-1.0_temp-1.0_decay-generic.hepmc .

# then you can make your own test.py for plotting or run jupyter notebook
jupyter notebook tutorial.ipynb
```

Conclusion/Discussion

Now everyone is an expert in simulating SUEPs

Easy to change: mediator and dark meson mass, temp, decay to SM

Harder to change: underlying aspects of the dark shower

Interesting extensions or projects?

self consistency checks, a la (2103.01238)

comparing SUEPs with intermediate phase space (2009.08981)

Additional References

A Robust Measure of Event Isotropy at Colliders
https://arxiv.org/abs/2004.06125
Spheres to Jets Tuning Event Shapes with 5d Simplified Models
https://arxiv.org/abs/2009.08981

Track-based triggers for unconventional signatures
LOI and SUEP track trigger efficiency studies