SUEPs

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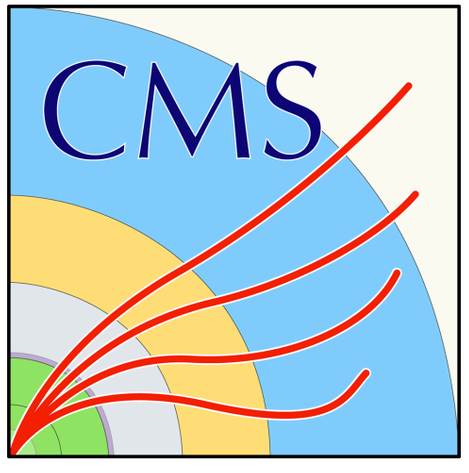
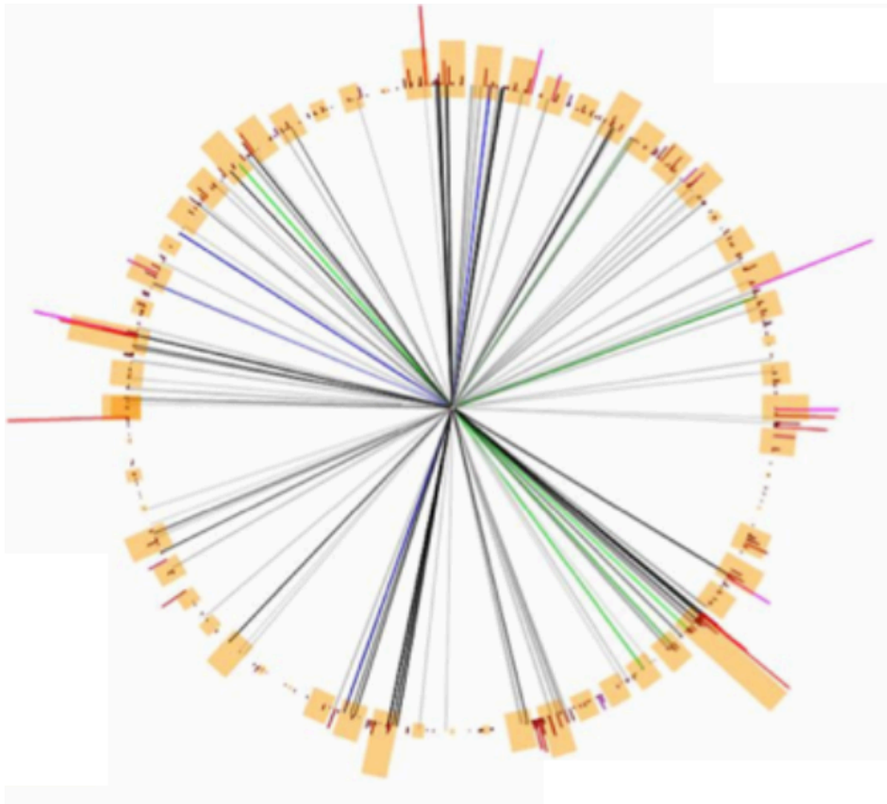
Snowmass Dark Showers

21 Jan 2021



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
  - SUEPs: 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



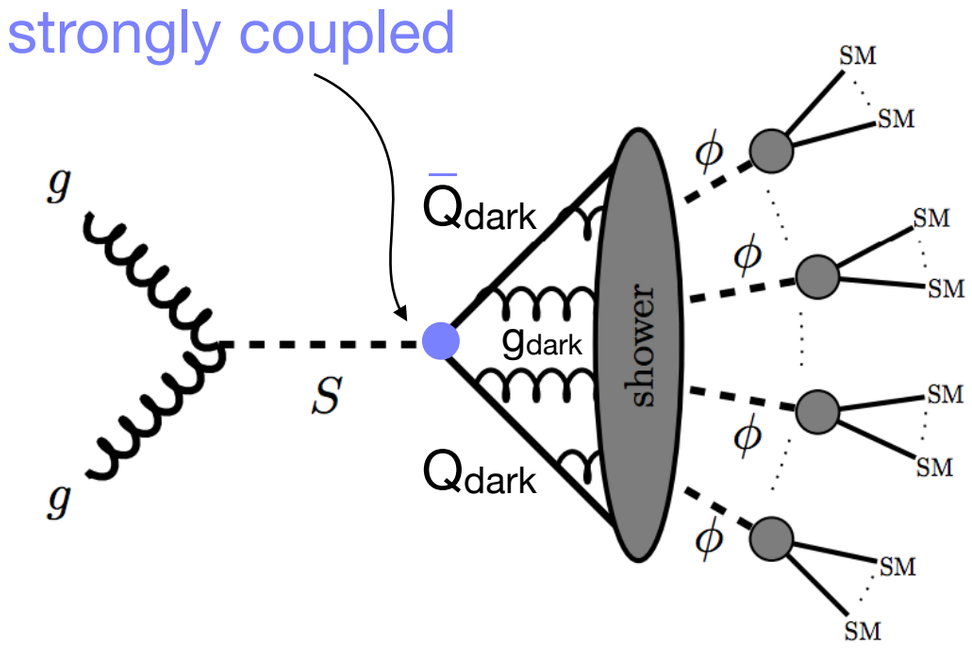
Simulating SUEPs

pythia 8 plugin from Simon Knapen
https://gitlab.com/simonknapen/suep_generator
Triggering Soft Bombs at the LHC

production via scalar mediator, S

dark shower to light dark mesons, ϕ

dark mesons decay promptly to Standard Model



*Possible to modify mediator and decay mode

Production

Production: scalar mediator via gluon gluon fusion

user specifies scalar mass

typical target: 100 GeV < m_S < 1 TeV

possible to add ISR, modify mediator, 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

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

- single flavor of final state dark mesons, ϕ
- dark meson momentum vectors drawn from a relativistic Maxwell Boltzmann distribution with temperature, T
- SUEP shower is boosted into lab frame and attached to event
- m_ϕ and T are set by the user
- 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

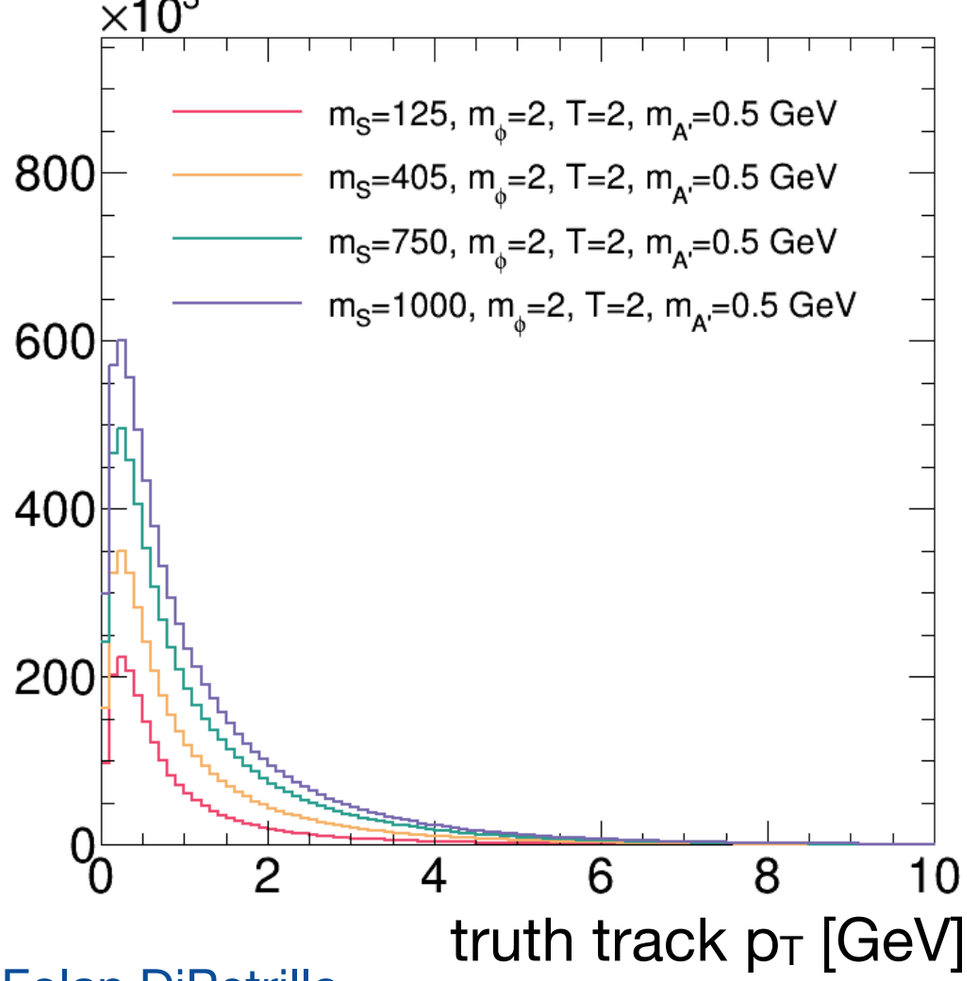
- Example decay cards provided for
  - $\phi \rightarrow$ dark photons $\rightarrow$ SM
  - $\phi \rightarrow$ qq-bar

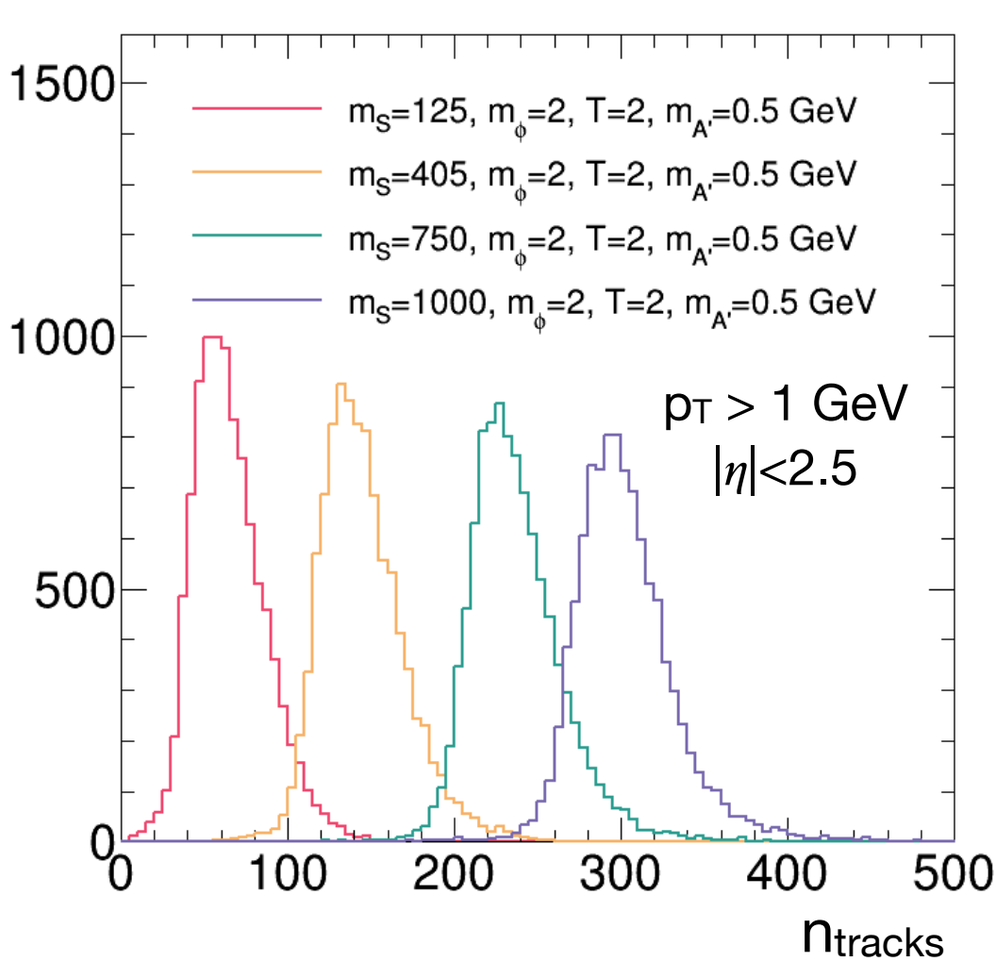
`decay_cards/decay_darkphoton.cmnd`

```
// This card provides the decay settings for the hidden mesons.
// See http://home.thep.lu.se/~torbjorn/pythia81html/ParticleDataScheme.html for syntax
// Please verify that the channels you choose are kinematically allowed for the meson mass you selected.
//
// In this example, we decay each dark meson two 2 dark photons (pdg code 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 tracks
  - spherical event shape
- Varying signal parameters
  - <u>scan scalar mass:</u> $n_{tracks} \sim m_S$
  - scan temperature: $n_{tracks} \sim 1/T$, track p_T increases with T

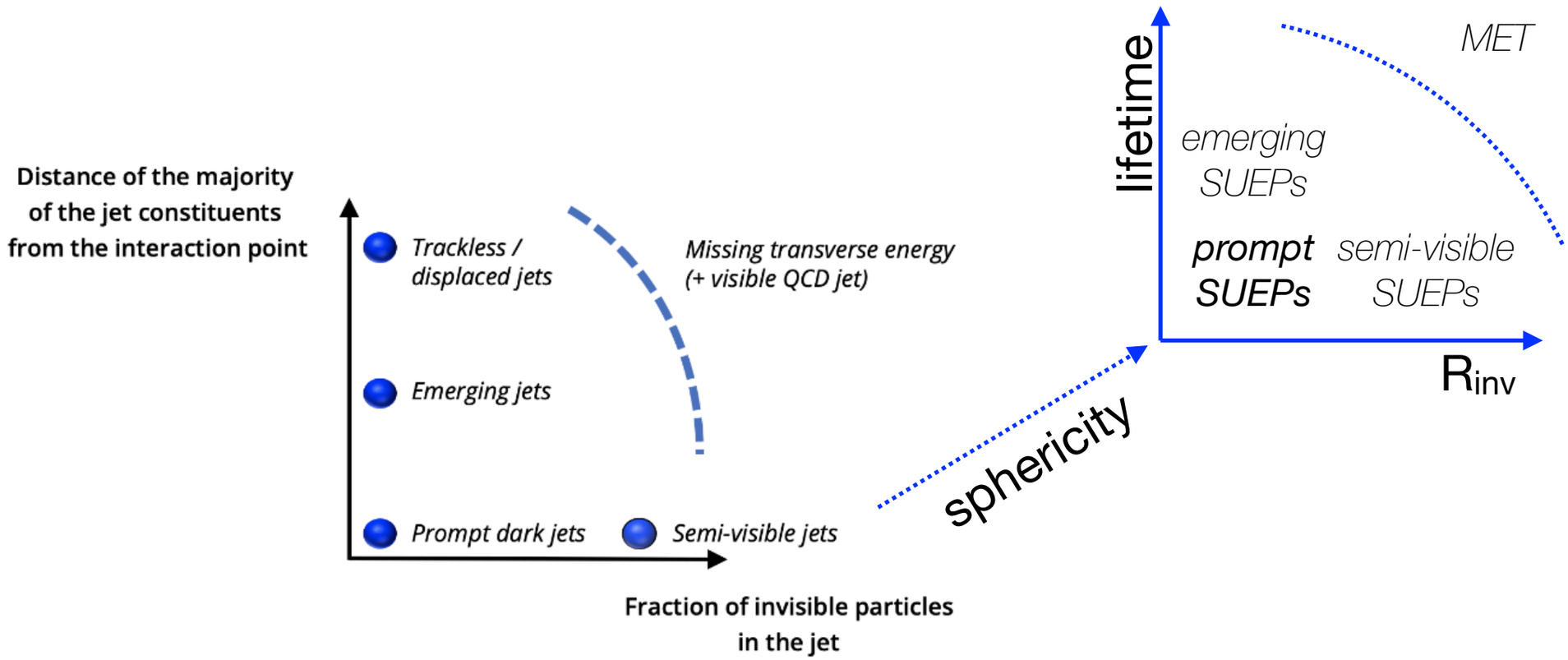




*10k signal events - not scaled by XS

Dark Shower Connections

Studying SUEPs would add another axis to Fig 1 of LOI



- there may be potential commonalities with other searches: depending on trigger strategy, SUEPs can be boosted into fat jets
- additional work would be necessary to study emerging/semi-visible SUEP signatures

Conclusion/Discussion

- Described SUEPs & pythia setup
- Interesting and uncovered phase space at the LHC
  - ongoing efforts in CMS and ATLAS
  - several CMS members participate in this group!
- Mild concern in the context of Snowmass
  - no public search specifically targeting SUEPs
  - difficult to make statements about expected LHC coverage
- What could still be interesting for this group
  - establish a clear set of SUEP benchmarks
  - better understand extensions/shortcomings of SUEP model(s)
  - study potential strategies/observables for LHC/HL-LHC
  - understand if there is any coverage from other searches

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
- Searching for QCD Instantons at Hadron Colliders - https://arxiv.org/abs/2010.02287
- How to discover QCD Instantons at the LHC - https://arxiv.org/abs/2012.09120
- Track-based triggers for unconventional signatures LOI and SUEP track trigger efficiency studies