Promptly decaying SUEP at the LHC

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Outline

- What are Soft Unclustered Energy Patterns (SUEP)
- VH $\rightarrow$ SUEP
- Simulation, Observables and Analysis
- Towards Unsupervised Machine Learning

Hidden Valley Models (HVM)

- Dark Gauge Group under which SM particles are not charged
- New, light hidden Sector particles not charged under SM
- Production and decay portals through higher dimensional operators with various UV completions possible
- Phenomenologically interesting: electroweak hierarchy, dark matter, matter-antimatter asymmetry and origin of neutrino masses [Knapen et al., 2021]
- Theoretically motivated: HVM arise in many top-down approaches, consistent with various popular solutions to the hierarchy problem [Strassler and Zurek, 2007]

Soft Unclustered Energy Patterns

- SUEP signatures are a subset of dark shower signatures can arise when the gauge group of the HVMs is confining. [Knapen et al., 2017, Knapen et al., 2021].
- SUEP-like event: $pp \to \mathcal{S} + X$, where $\mathcal{S}$ is a high multiplicity state of SM hadrons with an isotropic distribution of momenta and X is some other SM state associated to the SUEP production

How can they lead to SUEP?

SUEP ingredients:

- Models with a confining gauge group $\rightarrow$ Dark partons will undergo showering (Dark Shower) and Hadronize
- Quasi-conformal in energy range Q-Λ, where Q is the hard scale of the production event and Λ is the confining scale of the HVM.
- Large 't Hooft coupling ($\lambda \gg 1$) $\rightarrow$ parton momentum fraction $x \sim \frac{\Lambda}{Q}$ democratic distribution of dark parton momenta

Average multiplicity $\sim \frac{Q}{\Lambda}$.
If $\frac{Q}{\Lambda} \gg 1 \rightarrow$ high multiplicity $+\ x \ll 1 =$ SUEP! This can be described by a thermal distribution [Knapen et al., 2017]:

$$\frac{dN}{d^3\mathrm{p}} \sim \exp\left(-\sqrt{\mathrm{p}^2 + \mathrm{m}^2}/T\right) \tag{1}$$

where $T \sim \Lambda$.
Hadronization depends more on the details of the model, but in general $m \sim T$. Details of hadronization are large source of uncertainty.

Higgs→ SUEP in VH

- Triggering for SUEP in general challenging
- Higgs production mode is highly motivated, take advantage of VH for triggering
- Production: Effective operator $O_{production} = |H|^2 \partial^{2P} \phi_D^N$ where $N \gg 1$
  ϕ_D is the lightest Dark Hadron
- Decay: Gluon portal (not unique) Effective decay operators:

$$O_{decay} \sim G\tilde{G}\phi_D$$

  and/or

$$O_{decay} \sim GG\phi_D$$

  depending on if ϕ_D is a scalar or pseudo scalar.
- ϕ_D decay into gluons giving an SM rich hadron final state.

SUEP Cartoon

Our signal model is controled by T_{DH} and m_{DH}

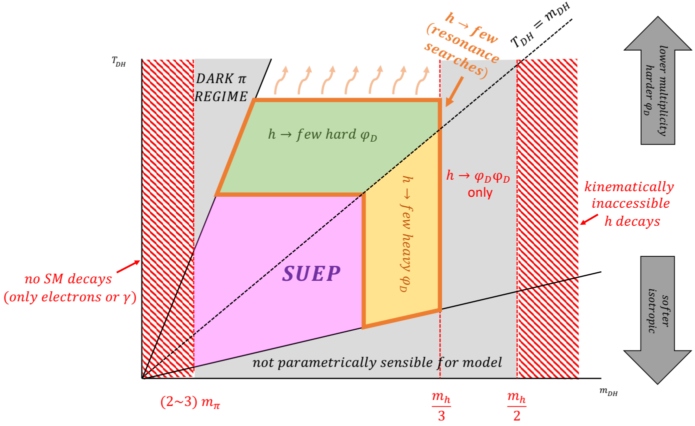


Figura: $h \rightarrow$ SUEP

Simulation Paramater Space

- We look at a range of $m_D \in [0.4, 10]$ GeV with $\frac{T}{m_D} \in [0.5, 4]$
- Used SUEP generator [Knapen 2018],
- Magraph 5 with Pythia 8 for 2,3,4-jet Background. 2-jet BG was dominant
- Used Delphes Charged tracks for analysis

Why Prompt SUEP?

Naively at these masses ($m_{Dh} \lessapprox$ *few* GeV) the decay to high multiplicity states would not be prompt.

- If the decay is prompt, $m_{Dh} \gtrapprox 10 GeV$ [Knapen et al., 2021] would generate harder jets and so could be searched for be easier to find using jet substructure techniques.
- Non-prompt decay generates displaced vertices and/or Long Lived SUEP

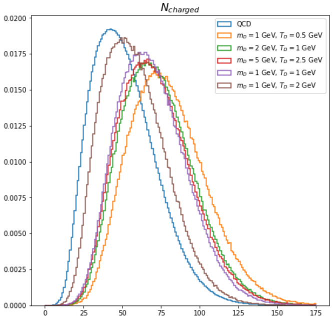
Our search's sensitivity is based on using only the charged track information. Maximally challenging scenario. **Combining it with other possible features of the signal will only enhance and/or broaden sensitivity.**

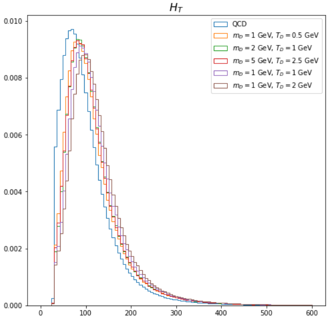
Observables and conventional cuts

Considering Higgs VH cross sections, For $Br(H \to Dark) \sim 0.1$, we need $\frac{e_S}{e_b} \sim 1000$

Used some conventional event level observables:

- Start by Using $N_{Charged}$, H_T, Lepton momenta

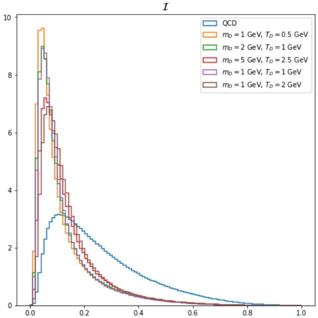


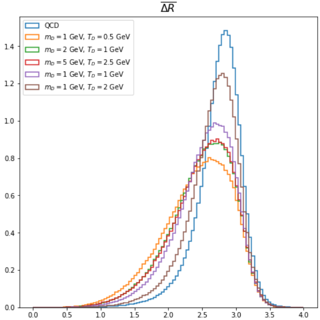


Picking the right observables is important!

Observables and conventional cuts

- Added [Cesarotti and Thaler, 2020] Event Isotropy $\mathcal{I}$ observable
- Introduce interparticle distance matrix representation for events , $\Delta R_{ij} = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}$ distance, and the average event level $\overline{\Delta R}$





Can do better using these observables, more on this in the next talk!

Can we do better with simple supervised learning?

- We can use a supervised model (few layer perceptron) on higher level observables ($N_{Charged}$, H_T,$\mathcal{I}$, $\overline{\Delta R}$, lepton P_T)
- Does well around model points where it's trained
- Is not effective away from the (m_{Dh}, T) point on which it's trained.
- Independent tuning for each training point in principle required
- Good candidate for **Unsupervised search** since that will not depend on knowledge of signal model-generation, tuning is independent of the signal

Outlook

- Further Theoretical model building always needed
- Probe other regions of parameter space, including Long Lived SUEP
- See next talk for more on unsupervised approach!

Cesarotti, C. and Thaler, J. (2020).
A robust measure of event isotropy at colliders.

Knapen, S., Griso, S. P., Papucci, M., and Robinson, D. J. (2017).
Triggering soft bombs at the lhc.
Journal of High Energy Physics, 2017(8).

Knapen, S., Shelton, J., and Xu, D. (2021).
Perturbative benchmark models for a dark shower search program.

Strassler, M. J. and Zurek, K. M. (2007).
Echoes of a hidden valley at hadron colliders.
Physics Letters B, 651(5-6):374–379.

Dark Shower Intuition+ Gluon Portal

- Each splitting will have energy

$$Q_i \sim \frac{Q}{2^i}$$

- Splitting finishes at

$$Q_{N_{final}} \sim \frac{Q}{2^{N_{final}}} \sim \Lambda$$

- Average multiplicity is $2^{N_{final}} \sim \frac{Q}{\Lambda}$
- For large 't Hooft Coupling, the momentum fraction carried by each parton will $x \sim \frac{\Lambda}{Q}$.

Therefore, for a large enough scale separation $\frac{\Lambda}{Q} \ll 1$, we get a high multiplicity, democratic distribution of dark partons.

$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{\alpha_2}{8\pi}\frac{1}{f_a} a G_{\mu\nu}\tilde{G}^{\mu\nu} - iy_{\psi_D} a\psi_D\psi_D^*$$

where a is a heavy elementary pseudo scalar.

SUEP Observable Plots

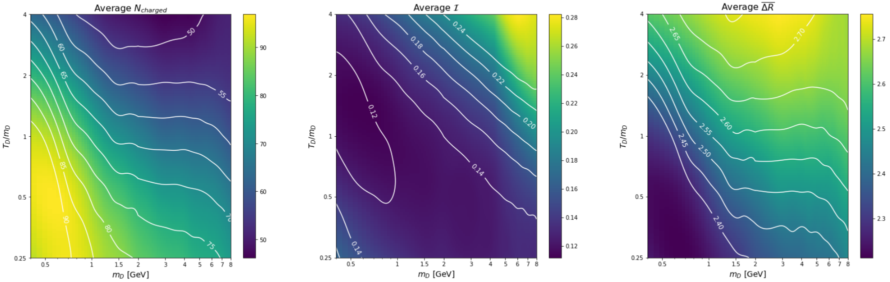


Figura: Average values of selected observables as a function of m_D and T_D for SUEP.

Signal/BG efficiency requirements + Conventional Cut numbers

- $\frac{S}{B} = \frac{\sigma_{Higgs} Br(H \to Dark) e_s}{\sigma_{BG} e_b}$
- σ_{Higgs} from W/Z+H is $\sim 300 fb$, $\sigma_{BG} \sim 3000 fb$ (2 jet sample).
- We want enough signal to beat the background systematics which are $\mathcal{O}(fewpercent)$
- For $Br(H \to Dark) \sim 0.1$, we need $\frac{e_S}{e_b} \sim 1000$ background efficiency of this cut on the post-trigger sample is 2.20%, while the signal efficiency varies from 31.8% at $m_D = 0.4$ GeV, $T_D = 0.4$ GeV to 1.1% at $m_D = 5$ GeV, $T_D = 20$ GeV.

Cutting on all the above observables for the post-trigger sample, yields $\frac{e_s}{e_b} \sim 14.4$ at $m_D = 0.4$ GeV, $T_D = 0.4$ whereas it's not effective for the other end of paramter space at $m_D = 5$ GeV, $T_D = 20$ GeV