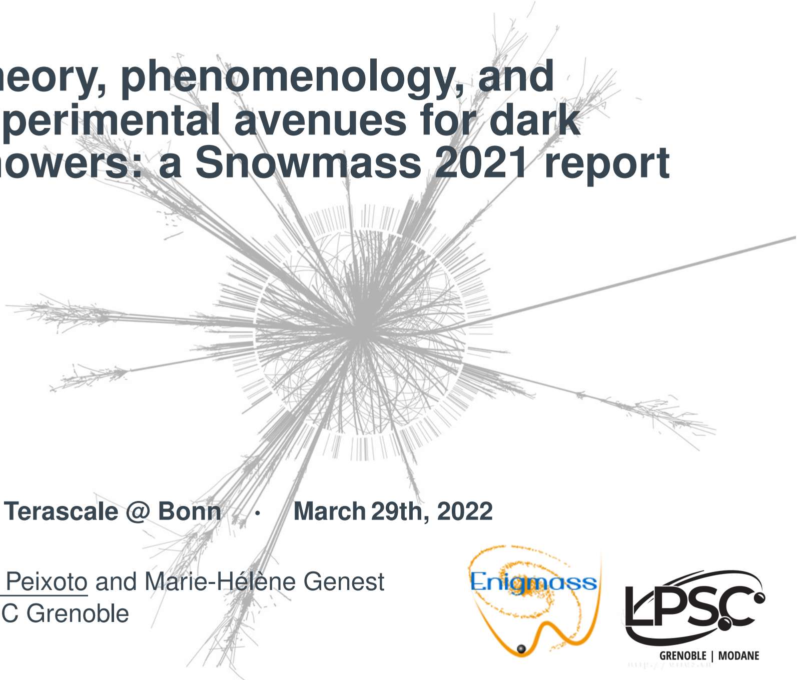
Theory, phenomenology, and experimental avenues for dark showers: a Snowmass 2021 report



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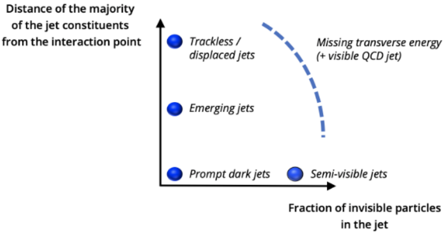
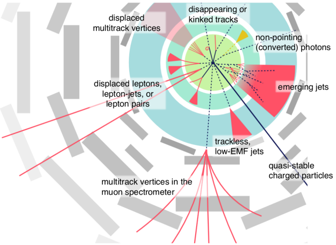
Dark showers

Snowmass project

Systematic survey of a class of dark sector models known as dark QCD models done by theorists and experimentalists (full report recently published):

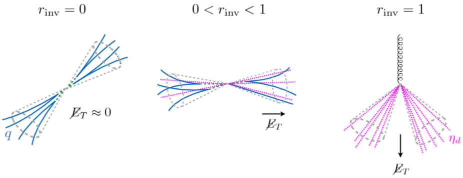
- **Theory:** QCD-like scenarios of dark sector and beyond
- **Phenomenology:** Benchmarks from the underlying physical parameters for semi-visible jets
- **Experiment:** Improvement of the search strategies

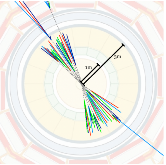




Theories of dark QCD
Theory

- Dark particles can then be produced at hadron colliders via a portal of communication between the Standard Model (SM) and the dark sector
- Dark jets properties determined by the dynamics of the dark sectors, namely the coupling strength, the ratio of unstable to stable dark hadrons inside the dark jets, and the mass scale of the dark hadrons
- Production through the *s*-channel with a *Z*' boson mediator or a new scalar via the *t*-channel
- Depending on the parameters of the theories, final states can contain semi-visible jets, lepton jets, emerging jets, soft-unclustered-energy patterns,...



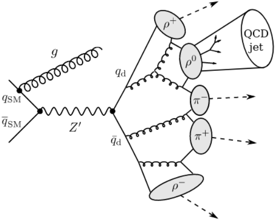


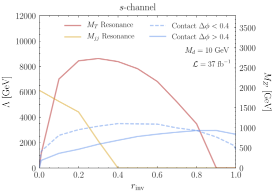
Contributors: Timothy Cohen and Christiane Scherb

Dark QCD with s-channel

Theory

- Assuming a portal coupling the dark sector to the SM quarks, the observables of interest will be jets and missing energy (likely to be aligned with the jets)
- Many models consider pairs of dark quarks being produced via a heavy resonance Z' also coupling to SM quarks
- Main parameters to be studied: the Z' mass, its couplings to visible and dark quarks $\alpha_{q,d}$, the dark sector shower (number of dark colors, dark flavors, and the scale of dark sector confinement Λ_d), the scale of the dark hadrons m_d and the average fraction of stable hadrons that are aligned with the visible jet r_{inv}

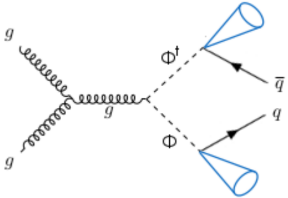




Contributors: Timothy Cohen and Christiane Scherb

Dark QCD with *t*-channel
Theory

- A *t*-channel mediator can also be introduced either via Minimal Flavour Violating models or by enhancing the SM gauge group by a dark flavour symmetry $SU_D(N_D)$ and introducing n_d dark quarks χ_D
- Focusing on the pair production where both mediators decay subsequently to a visible and a dark quark forming a SM and a dark jet (with showering and hadronization)
- Depending on the lifetime of the dark pions, three different final states are possible: final states with four prompt jets, the dark pions have intermediate lifetimes resulting in emerging jets and the dark pions are stable on collider scales being recorded as missing energy



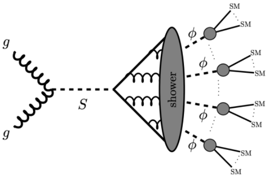
Contributors: Timothy Cohen and Christiane Scherb

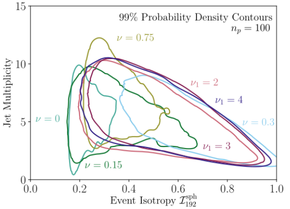
Soft-Unclustered-Energy Patterns

Theory

SUEPs events are usually characterized by a high multiplicity of soft particles distributed quasi-isotropically in their rest frame

- A hidden valley (HV) of new physics is accessed via a heavy scalar mediator, further decaying into a high multiplicity of light HV mesons of a single flavor ϕ (m_S, m_ϕ, T)
- Taking into account the global radiation pattern, event shape observables can serve as useful analyses tools
- Defined using the Energy Mover's Distance, a new observable called event isotropy aims to study deviations from truly isotropic events
  $\Rightarrow$ Not strongly correlated with final state multiplicity, or reconstructed number of jets

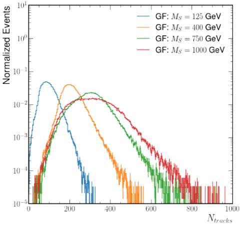


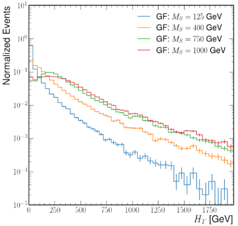


Contributors: Cari Cesarotti, Carlos Erice, Karri Folan DiPetrillo, Chad Freer, Luca Lavezzo, Christoph Paus and Matt Strassler

Soft-Unclustered-Energy patterns
Theory

- Without high momentum final state particles, SUEPs with all-hadronic final states can easily be mistaken for pile-up collisions
- Trigger strategies based on the scalar sum of hadronic activity (H_T) in the event can be used to target mediators produced via gluon fusion
- After trigger and reconstruction, the two most powerful observables are the characteristic high track multiplicity and the isotropic distribution of such tracks
- Recent studies present anomaly detection techniques as a generic way to search for new physics with SUEP signatures with promising sensivities for the HL-LHC





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In the $N_f = 0$ limit for $SU(N_c)$ Yang-Mills theories, the only hadronic states that form below the confinement scale are glueballs, composite gluon states

- A recent public Python package, GlueShower, allows the simulation of dark glueball showers produced from an initial pair of dark gluons
- Two qualitatively different hadronization possibilities included: a more physically motivated jet-like assumption and a more exotic plasma-like option with colour-singlet gluon-plasma- states
- Preliminary studies performed with a set of 4 benchmarks points to identify the range of physically reasonable glueball hadronization possibilities
- Despite the wide range of possibilities for hadronization that are considered, most glueball observables are predicted within an $\mathcal{O}(1)$ factor

Contributors: David Curtin, Caleb Gemmell and Christopher B. Verhaaren

Simulation of dark showers

Phenomenology

Focusing on the semi-visible jets, possible pathways for consistent theory frameworks were discussed:

- Tentative to build coherent benchmarks

Regime	N_c, N_f	Λ_v [GeV]	**Q**	m_{π_v} [GeV]	m_{ρ_v} [GeV]	Stable dark hadrons	Dark hadron decays
$m_{\pi_v} > m_{\rho_v}/2$	3,4	10	(-1,2,3,-4)	17	31.77	All π_v	$\rho_v^0 \to q\bar{q}$ $\rho_v^\pm \to \pi_v^\pm q\bar{q}$
$m_{\pi_v} < m_{\rho_v}/2$	3,3	5	Various	3	12.55	$0/1/2\pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$
	3,3	10	Various	6	26	$0/1/2\ \pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$
	3,3	50	Various	30	125.5	$0/1/2\ \pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$

- Lattice computations also considered as by fixing mass ratios with respect to the confinement scale Λ
- Overview of the decays of dark hadronic bound states that are either stable (decaying within the dark sector) or decay to final states including SM particles

Contributors: Suchita Kulkarni, Seán Mee and Matt Strassler

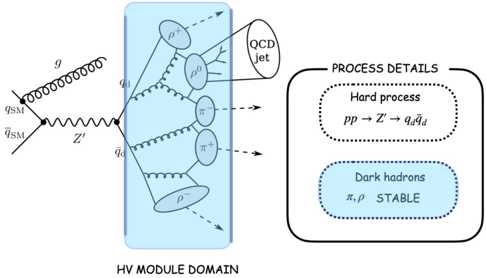
New Pyhtia Hidden Valley module

Phenomenology

An updated Pythia8 Hidden Valley module is available:

- **Full flavour splitting for dark mesons:** now possible to access all PDGIDs 4900ij3 (with decays, masses and lifetimes)
- Possibility to add a suppression factor in the production of the highest flavour diagonal meson
- Some changes of the parameters in fragmentation routine

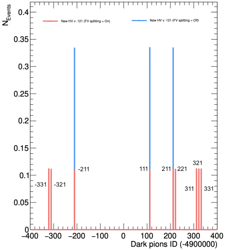
Study performed targetting the flavour splitting parameters validation focusing on the $pp \to Z' \to q_d\bar{q}_d$ process ($m_{Z'}$=1 TeV, Λ_d=10 GeV)

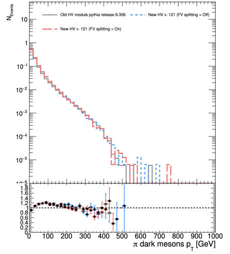


Contributors: Suchita Kulkarni, Seán Mee and Matt Strassler

New Pyhtia Hidden Valley module

Phenomenology





Validation executed considering the N_c=3 with N_f=3 and N_f=8 cases:

- With flavour splitting, 9 pseudo-scalars and 9 vectors dark mesons for the N_f=3 scenario while 64 different dark mesons states can be accessed with N_f=8
- For both cases, dark mesons present lower multiplicity and softer p_T due to new p_T suppression for mini-strings fragmentation with the new module
- In general, similar distributions for the new module with flavour splitting switched on and off and no relevant impact on event kinematic variables

Contributors: Guillaume Albouy, Cesare Cazzaniga, Annapaola de Cosa, Florian Eble, Marie-Hélène Genest, Nicoline Hemme, Suchita Kulkarni, Stephen Mrenna, Ana Peixoto, Akanksha Singh, Torbjörn Sjöstrand and Matt Strassler

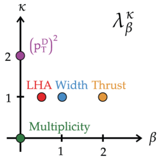
Jets substructure

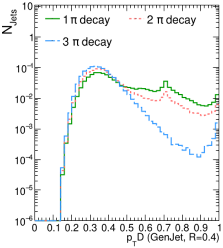
Phenomenology

Study considering a 3-flavour model with dark pion decays to the SM via a 1 TeV Z' boson having 1, 2 or 3 diagonal pions unstable:

$$\lambda_\beta^\kappa = \sum_{i \in jet} z_i^\kappa \left(\frac{\Delta R_{i,jet}}{R} \right)^\beta$$

- Check differences in the jets substructure observables between different vector meson production fractions of 50% and 75%
- Using generator-level jets clustered with the inclusive anti-k_t algorithm with R=0.4
- Several category of jet shape variables considering generalized angularities: jet momentum dispersion p_T^D ($\approx \sqrt{2p_\mathrm{T}^2}/(2p_\mathrm{T})=1/\sqrt{2}$), girth and minor/major axes
- Similar study performed at reco-level to identify the best substructure observables to tag dark jets efficiently

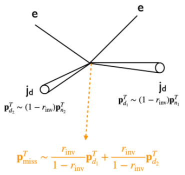


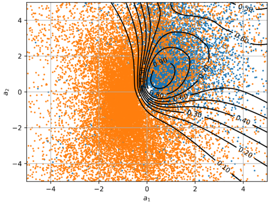


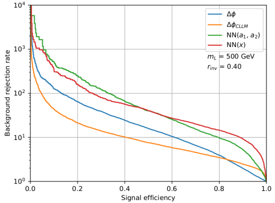
Contributors: Cesare Cazzaniga, Florian Eble, Aran Garcia-Bellido, Nicoline Hemme and Nukulsinh Parmar

Event-level variables

Experiment







Searches for semi-visible jets consist of jets of visible hadrons intermixed with invisible stable particles:

- Tagging semi-visible jets and exploiting a special relation between the azimuthal direction of those jets and missing transverse momentum have been pursued up to now
- Definition of new event-level variables can increase the sensitivity of such searches
- By knowing that the semi-visible jets are responsible for most of p_T^{miss} in signals, such variable can be transformed into two as $p_T^{miss} = a_1\ p_T^{d1} + a_2\ p_T^{d2}$

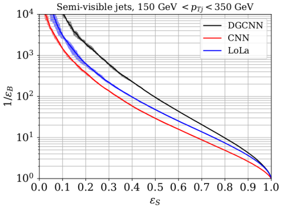
Contributors: Hugues Beauchesne and Giovanni Grilli di Cortona

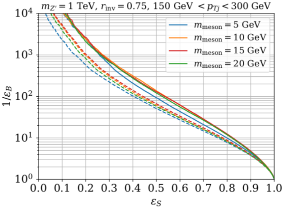
Graph Neural Networks

Experiment

The potential of deep neural networks on the identification of semi-visible jets from dark showers is also promising

- A Dynamic Graph Convolutional Neural Network (DGCNN) was used to distinguish dark shower jets from QCD jets
- Different parameter values studied to evalute the classification performance of the DGCNN (r_{inv}, m_{meson}, etc) $\Rightarrow$ Effect more substantial for the dark meson masses
- Impact on the sensitivity of an experimental search for dark showers by applying a DGCNN as a semi-visible jet tagger also studied $\Rightarrow$ Improvement by more than one order of magnitude



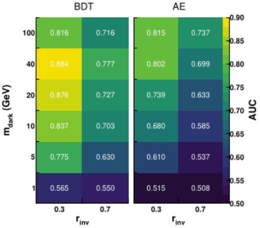


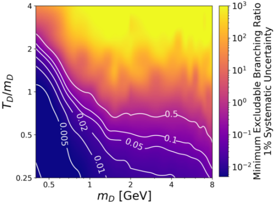
Contributors: Elias Bernreuther

Autoencoders
Experiment

Large total number of unknown theory parameters leads to a vast model space with a huge number of possible scenarios:

- Autoencoders can help by providing anomalous jets taggers: robust against both detector effects and details of the model implementation
- Comparison between Boosted Decision Trees and Autoencoders performed for the scenario with semi-visible jets where a fraction of jet constituents is invisible to the detector using high-level properties of jets
- Analyses targetting SUEPs where the background events are soft and highly isotropic QCD events ⇒ Possible to be probed at the HL-LHC



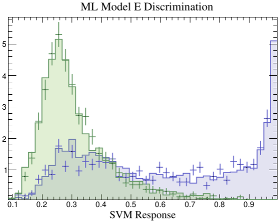


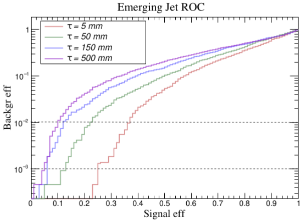
Contributors: Annapaola de Cosa, Jeremi Niedziela, Kevin Pedro, Jared Barron, David Curtin, Gregor Kasieczka, Tilman Plehn, Aris Spourdalakis

Trigger on emerging jets

Experiment

- Focusing on a Z' that couples to the quark current in the SM and the dark quark current which typically does not include additional hard jets $\Rightarrow$ typical H_T considerably lower than typical trigger thresholds at the LHC experiments
- Two main strategies are explored to increase the trigger efficiency:
  - Exploiting the possibility of SM radiation from the initial state (additional hard jets can be triggered)
  - Implementing new triggers using modern machine learning techniques as Support Vector Machines to distinguish signal from the dominant $b\bar{b}$ background





Summary

- Strongly-interacting dark sectors are an exciting class of scenarios for a considerable community of theorists, phenomenologists and experimentalists
- Overview of existing efforts and of the signature landscape for QCD-like and beyond scenarios
- Possible pathways for consistent theory frameworks, especially concentrating on semi-visible jets, studied in detail in a tentative to address the impossibility to set consistent UV and IR parameters based purely on perturbative analysis
- Improvements to the Pythia8 Hidden Valley module motivated by the theory being later validated for different viable scenarios with high-level variables
- Sensitivity of the LHC search strategies proven to be increased by profiting from machine learning, trigger considerations and the definition of new event level variables

Thanks for the attention!

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