Casting a ParticleNet to catch dark showers

Elias Bernreuther

RWTH Aachen University

based on **arXiv:2005.xxxxx**

with Thorben Finke, Felix Kahlhoefer, Michael Krämer and Alexander Mück

28 April 2020

RTG 2497

Physics of the Heaviest Particles at the LHC

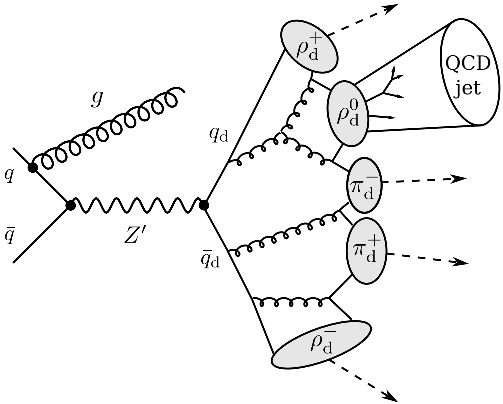
TRR 257 - Particle Physics Phenomenology
after the Higgs Discovery

Strongly interacting dark sectors

- **What if the dark sector resembles QCD?**
  $\Rightarrow$ DM could be meson/baryon in confining dark sector
- Cosmology: relic density from interactions within dark sector
  Hochberg et al., 1411.3727
- Astrophysics: possible resolution of DM small-scale problems (SIDM)
  Hochberg et al., 1402.5143
- **Novel LHC phenomenology**:
  - dark showers
  - semi-visible jets — Cohen et al., 1707.05326
  - emerging jets — Schwaller et al., 1502.05409

Dark showers at the LHC

- Dark $SU(3)$, dark pion DM, consistent cosmology EB et al., 1907.04346
- Production of dark quarks at the LHC via heavy vector mediator
- Shower and hadronisation in dark sector (Pythia Hidden Valley)



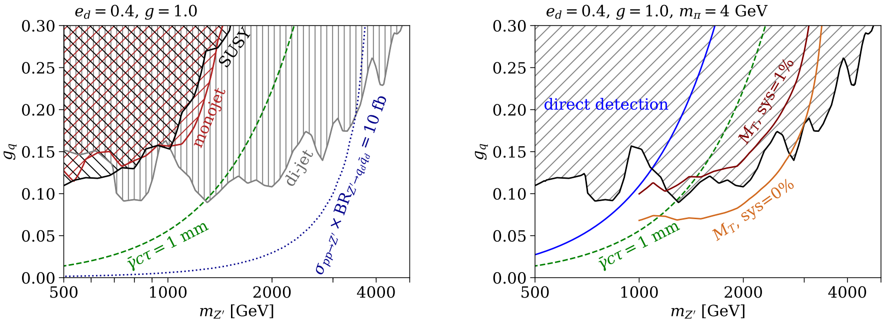
$m_{Z'} \sim \mathcal{O}(\mathrm{TeV})$, $m_\pi \sim m_\rho \sim \mathcal{O}(\mathrm{GeV})$

- 10 - 20 dark mesons in an event
- Most escape the detector as $\not{E}_T$
- ρ_d^0 decay to visible jets

⇒ **Semi-visible jets**

⇒ Jets+$\not{E}_T$, often aligned

Existing and prospective LHC searches



Two classes of events:

- If one dark shower stays invisible:
  ⇒ Limits from existing monojet and SUSY searches
- If both dark showers become partly visible:
  ⇒ Prospective semi-visible jet search: bump hunt in M_T for small $\Delta\phi$

Cohen et al., 1707.05326

improves existing limits only under optimistic assumptions

Can we do better with machine learning?

- Proposed semi-visible jet search does not use jet substructure
- Semi-visible jets differ substantially from QCD

⇒ **Train a neural network classifier to distinguish dark showers from QCD**

- Wide range of supervised and unsupervised ML approaches for jet classification, most commonly benchmarked on top tagging
  Kasieczka et al., 1902.09914
  For example Convolutional Neural Networks on jet images

- Dark showers more similar to QCD than tops: varying number of light dark mesons with varying missing energy between

Dynamic Graph CNN

- Originally from computer vision — Wang et al., 1801.07829
- Recently used as jet tagger: ParticleNet — Qu, Gouskos, 1902.08570

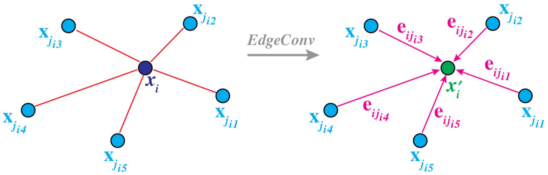
Jets as point clouds

- Every constituent is a point in a high-dimensional feature space
- No particular ordering

Edge convolution

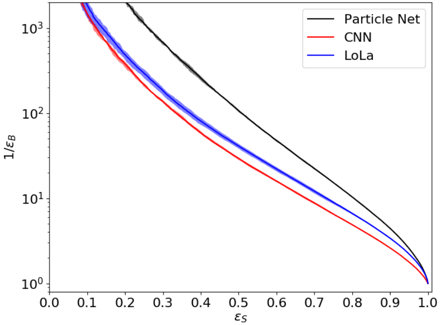
- For each point construct graph of k nearest neighbours
- Carry out convolution over edges (features of pairs of neighbours)
- $x_i' = \frac{1}{k}\sum_{j=1}^{k} h_\Theta(x_i, x_{i_j})$

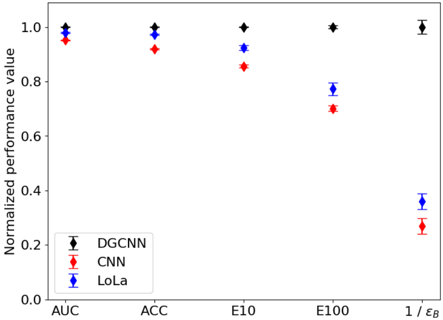
  with points $x_i \in \mathbb{R}^F$ and edge function $h_\Theta : \mathbb{R}^F \times \mathbb{R}^F \to \mathbb{R}^{F'}$



Wang et al., 1801.07829

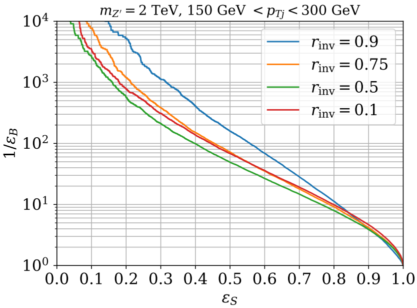
DGCNN performance in comparison to other networks

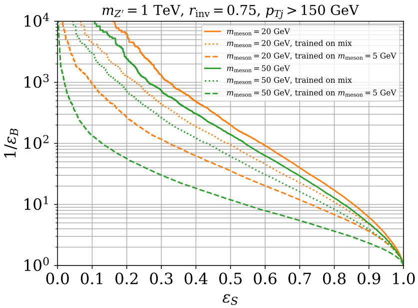




- Signal: semi-visible jets from dark showers, background: QCD jets
- DGCNN outperforms CNN operating on jet images as well as LoLa on 4-vectors
- Advantage of DGCNN is larger than for tops: dark shower identification the more difficult problem

Varying dark sector parameters: r_{inv} and m_ρ





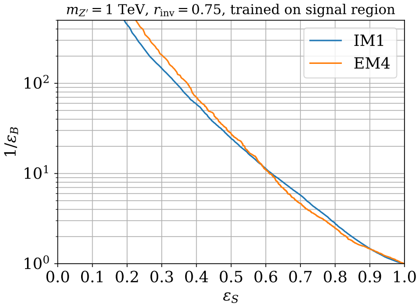
- Invisible fraction r_{inv} of shower can differ from 0.75
- Dark showers with larger r_{inv} easier to identify (more unlike QCD), once p_T is factored out
- Performance depends sensitively on dark meson mass

  $\Rightarrow$ mixed training or parametrised network

Applied to monojet analysis

By how much can we improve an analysis with our dark shower tagger?
⇒ **Monojet search as example** ATLAS-CONF-2017-060

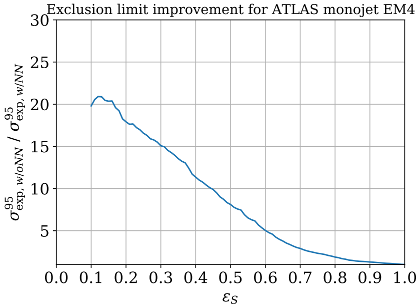
- Train on dark showers and dominant background (Z+jets), separately for each signal region

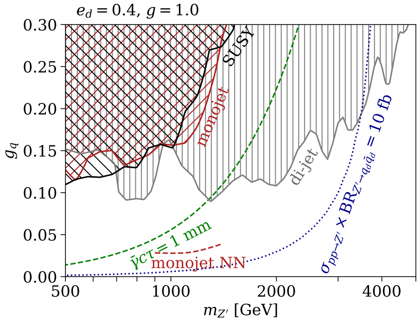


- Apply tagger after ordinary monojet cuts
- Require at least one jet tagged as dark shower

Sensitivity improvement and expected limit

Preliminary:





- Highly suppressed background, uncertainty becomes statistics-dominated
- Substantial increase in sensitivity
- Can bridge gap to displaced regime

Conclusions

- Strongly interacting dark matter is a well motivated scenario predicting exciting new LHC signatures
- Difficult to identify with conventional methods
- Great opportunity for machine learning
- Graph nets seem particularly suited to this task
- Can increase the sensitivity of searches by a lot
- Still on the lookout for an unsupervised technique that works here . . .

Backup

Model setup

$$SU(3)_{\mathrm{dark}} \times U(1)'_{\mathrm{mediator}}$$

- 2 flavours of dark quarks q_{d}

- Z' mediator $\sim \mathcal{O}(\mathrm{TeV})$ coupling to q_{SM} and q_{d}

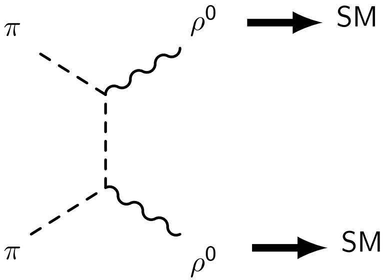
confinement at Λ_{d}

- π_{d}^0, $\pi_{\mathrm{d}}^{\pm}$, ρ_{d}^0, $\rho_{\mathrm{d}}^{\pm} \sim \mathcal{O}(\mathrm{GeV})$
- **Dark pions are DM (stable)**

- $Z'\pi_{\mathrm{d}}^{+}\pi_{\mathrm{d}}^{-}$, $Z'\rho_{\mathrm{d}}^{+}\rho_{\mathrm{d}}^{-}$ coupling
- Z'-ρ_{d}^0 mixing $\Rightarrow$ ρ_{d}^0 **unstable**

Freeze-out

- ρ_d in equilibrium in early Universe if $\Gamma_{\rho^0} > H$
- π_d-ρ_d decoupling sets DM relic density
- Dominant freeze-out process: $\pi_\mathrm{d}\pi_\mathrm{d} \to \rho_\mathrm{d}\rho_\mathrm{d}$ (forbidden DM, D'Agnolo et al., 1505.07107)

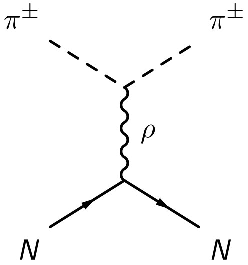


$$\sigma_{\pi\pi\to\rho\rho} \propto \frac{g^2}{m_\pi^2}\, e^{-2\Delta x_f}$$

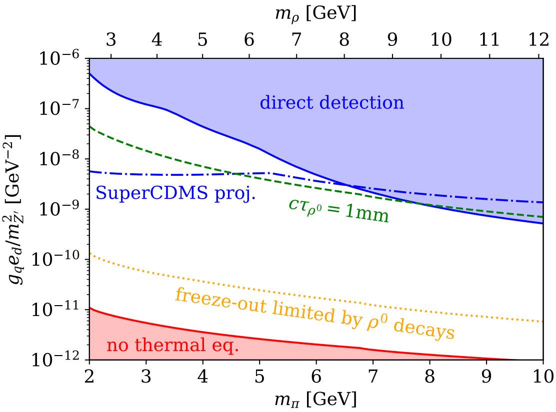
$$\Delta = \frac{m_\rho - m_\pi}{m_\pi} \sim 0.2 \text{ - } 0.5$$

- Relic density can be easily produced by adjusting m_ρ / m_π.

Direct detection



$$\sigma^{\mathrm{SI}} \propto \frac{e_d^2 g_q^2}{m_{Z'}^4}$$



Combination of CRESST-III, CDMSLite, PICO-60, PandaX and XENON1T

Dark $SU(3)$

The Lagrangian of the underlying dark $SU(3)$ gauge theory coupled to Z' reads

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a} + \overline{q_\mathrm{d}} i \not{D} q_\mathrm{d} - \overline{q_\mathrm{d}} M_q q_\mathrm{d} \\ - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} m^2_{Z'} Z'_\mu Z'^\mu - g_q \, Z'_\mu \sum_{q_\mathrm{SM}} \overline{q_\mathrm{SM}} \gamma^\mu q_\mathrm{SM} \ ,$$

where $q_\mathrm{d} = (q_{\mathrm{d},1}, q_{\mathrm{d},2})$ and $M_q = \mathrm{diag}(m_q, m_q)$. The dark quark covariant derivative has the form

$$D_\mu q_\mathrm{d} = \left(\partial_\mu + i g_D A_\mu + i e_D Z'_\mu Q \right) q_\mathrm{d} \ ,$$

Chiral EFT

The chiral EFT Lagrangian (up to fourth order in the pion fields) is given by

$$\begin{aligned}\mathcal{L}_{\mathrm{EFT}} &= \mathrm{Tr}\left(D_\mu \pi D^\mu \pi\right) - \frac{2}{3f_\pi^2}\mathrm{Tr}\left(\pi^2 D_\mu \pi D^\mu \pi - \pi D_\mu \pi \pi D^\mu \pi\right) \\ &+ m_\pi^2 \mathrm{Tr}\left(\pi^2\right) + \frac{m_\pi^2}{3f_\pi^2}\mathrm{Tr}\left(\pi^4\right) + \mathcal{O}\left(\frac{\pi^6}{f_\pi^4}\right) \\ &- \frac{1}{4}\mathrm{Tr}\left(V_{\mu\nu}V^{\mu\nu}\right) + m_V^2 \mathrm{Tr}\left(V^2\right) - \frac{e_\mathrm{d}}{g} Z'_{\mu\nu}\mathrm{Tr}\left(Q V^{\mu\nu}\right) \ . \qquad (1)\end{aligned}$$

The pion covariant derivative is given by

$$D_\mu \pi = \partial_\mu \pi + ig\left[\pi, V_\mu\right] + ie_\mathrm{d}\left[\pi, Q\right] Z'_\mu \ .$$

Mixing

$$\begin{pmatrix} \tilde{Z}' \\ \tilde{\rho}_0 \end{pmatrix} = \begin{pmatrix} \sec\epsilon & \sin\epsilon \, \frac{m_\rho^2}{m_{Z'}} \\ -\tan\epsilon + \frac{1}{2}\sin 2\epsilon \, \frac{m_\rho^2}{m_{Z'}^2} & 1 - \sin^2\epsilon \, \frac{m_\rho^2}{m_{Z'}^2} \end{pmatrix} \begin{pmatrix} Z' \\ \rho^0 \end{pmatrix} , \qquad (2)$$

where $\epsilon = \arcsin(2\, e_{\mathrm{d}}/g)$.

$$\mathcal{L}_{\mathrm{EFT}} \supset \frac{2\, e_{\mathrm{d}}\, g_q}{g} \frac{m_\rho^2}{m_{Z'}^2} \rho_\mu^0 \sum_{q_{\mathrm{SM}}} \overline{q_{\mathrm{SM}}} \gamma^\mu q_{\mathrm{SM}} \, . \qquad (3)$$

$$\mathcal{L}_{\mathrm{EFT}} \subset \left(-2\, e_{\mathrm{d}} \sqrt{1 - \frac{4\, e_{\mathrm{d}}^2}{g^2}} \frac{m_\rho^2}{m_{Z'}^2} Z'_\mu + g\, \rho_\mu^0 \right) \left[\pi^+ \left(\partial^\mu \pi^- \right) - \left(\partial^\mu \pi^+ \right) \pi^- \right] \, . \qquad (4)$$

Dark meson stability

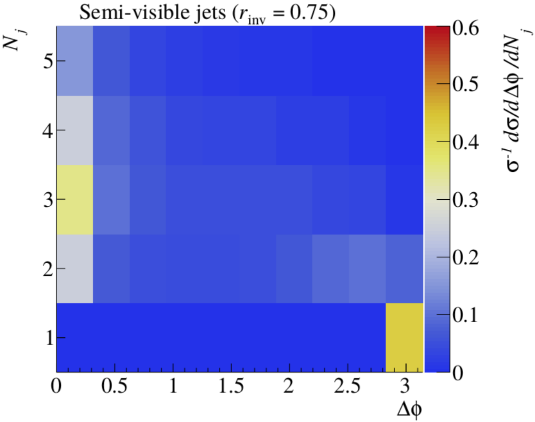
- Charged pions stable
- π^0 generically unstable
  - $\rightarrow$ extremely dangerous in early universe (CMB, BBN, relic density, ...)
  - $\rightarrow$ stabilised by G_d-parity if N_F even and $Q \propto \mathrm{diag}(1, -1)$
- $\rho^\pm$ effectively stable if $m_\rho < 2m_\pi$ (tiny three-body decay width)

- ρ^0-Z' **mixing induces** ρ^0 **decays to** $q_{\mathrm{SM}}\bar{q}_{\mathrm{SM}}$

$$\rightarrow \quad c\tau_{\rho^0} \approx 3.2\ \mathrm{mm} \times \left(\frac{g_q}{0.01}\right)^{-2} \left(\frac{e_d}{0.4}\right)^{-2} \left(\frac{m_\rho}{5\ \mathrm{GeV}}\right)^{-5} \left(\frac{m_{Z'}}{1\ \mathrm{TeV}}\right)^{4}$$

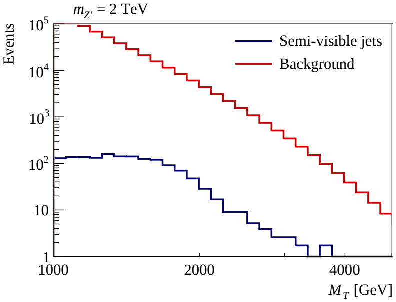
Semi-visible jets

- Signature: jets + $\not\!\!E_T$, but with a special twist
- Angular separation $\Delta\phi = \min_{i\leq 4}\left\{\Delta\phi_{j_i,\not E_T}\right\}$: $\not\!\!E_T$ often aligned with jet



Prospective search for semi-visible jets

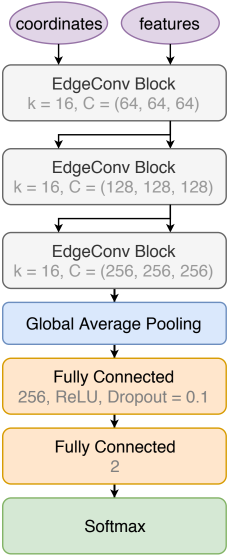
- Peak in M_{jj} washed out by variation in dark meson production
- Instead **search for peak in** M_T [Cohen et al. 1707.05326]:
  - Recluster jets into two large jets ($R = 1.1$)
  - Inverted angular cut: $\Delta\phi < 0.4$
  - Bump hunt in $M_T = \left(M_{jj}^2 + 2\left(\sqrt{M_{jj}^2 + p_{Tjj}^2}\,\not{E}_T - \vec{p}_{Tjj} \cdot \vec{\not{E}}_T\right)\right)^{1/2}$
- Backgrounds from Cohen et al. [1707.05326]



DGCNN architecture

Architecture (based on ParticleNet)

- Stacked EdgeConv blocks
  - Input features for each constituent: $\Delta\eta$, $\Delta\phi$, $\log p_T$, $\log E$, $\log(p_T/p_T(\text{jet}))$, $\log(E/E(\text{jet}))$, ΔR
  - k nearest neighbours based on η and ϕ in first block
  - in later blocks based on distance in new feature space $\Rightarrow$ dynamic GCNN
- Finally fully-connected layers for classification



Qu, Gouskos, 1902.08570