

Strongly interacting dark sectors in the early Universe and at the LHC

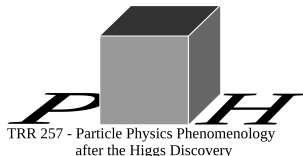
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based on [arXiv:1907.04346](https://arxiv.org/abs/1907.04346)

with F. Kahlhoefer, M. Krämer, P. Tunney

14 August 2019



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

- 2 flavours of dark quarks q_d
- Z' mediator $\sim \mathcal{O}(\text{TeV})$ coupling to q_{SM} and q_d



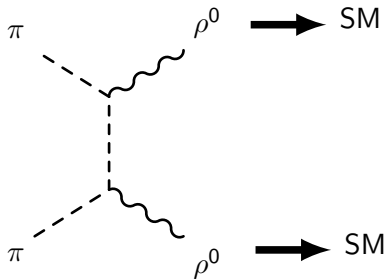
confinement at Λ_d



- $\pi^0, \pi^\pm, \rho^0, \rho^\pm \sim \mathcal{O}(\text{GeV})$
- **Dark pions are DM** (stable)
[Berlin et al., 1801.05805]
- $Z'\pi^+\pi^-, Z'\rho^+\rho^-$ coupling
- $Z'-\rho^0$ mixing $\Rightarrow \rho^0 \rightarrow q_{\text{SM}}\bar{q}_{\text{SM}}$

Freeze-out

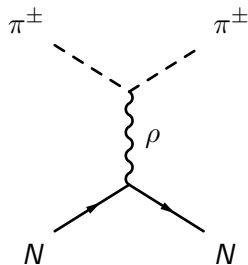
- ρ in equilibrium in early Universe if $\Gamma_{\rho^0} > H$
- π - ρ decoupling sets DM relic density
- Dominant freeze-out process: $\pi\pi \rightarrow \rho\rho$ (forbidden DM)



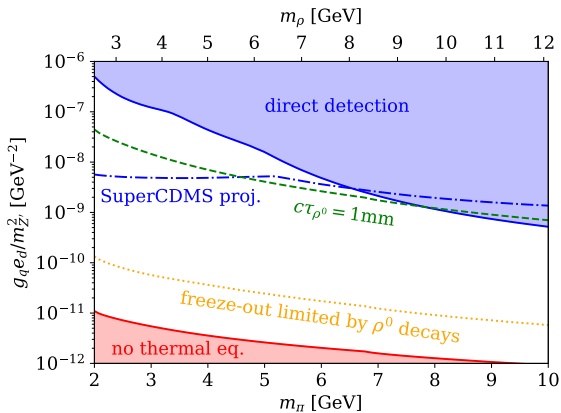
$$\sigma_{\pi\pi \rightarrow \rho\rho} \propto \frac{g^2}{m_\pi^2} e^{-2\Delta x_f}$$
$$\Delta = \frac{m_\rho - m_\pi}{m_\pi} \sim 0.2 - 0.5$$

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

Direct detection



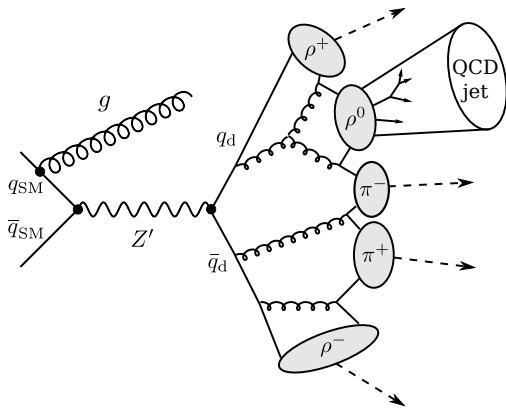
$$\sigma^{\text{SI}} \propto \frac{e_d^2 g_q^2}{m_{Z'}^4}$$



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

Dark showers

- At LHC resonant Z' production
- Then either $Z' \rightarrow q_{\text{SM}}\bar{q}_{\text{SM}}$ (di-jet) or ...
- Production of dark quarks: $pp \rightarrow Z' \rightarrow q_d\bar{q}_d$
- Shower and hadronisation in dark sector (PYTHIA HIDDEN VALLEY)

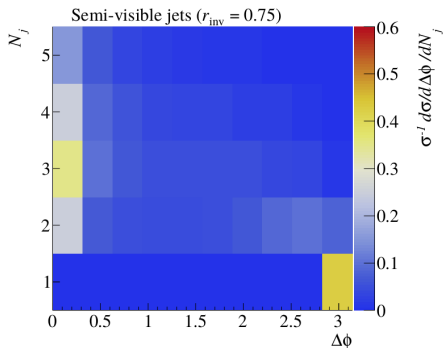


- $\mathcal{O}(20)$ dark mesons
 - ρ^0 decay to SM jets
 - Other dark mesons are \cancel{E}_T
- \Rightarrow Semi-visible jets

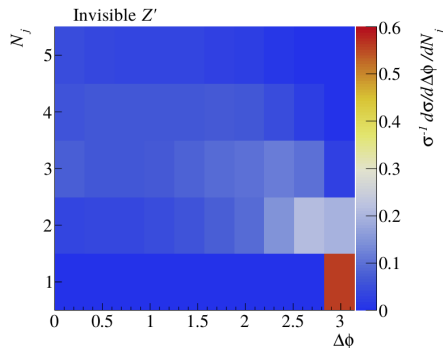
Semi-visible jets

- Signature: jets + \cancel{E}_T
- Characteristic kinematics
- E.g. angular separation $\Delta\phi = \min_{i \leq 4} \{ \Delta\phi_{J_i, \cancel{E}_T} \}$

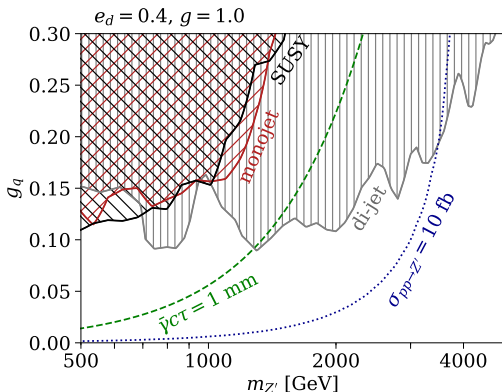
Semi-visible jets



Monojet

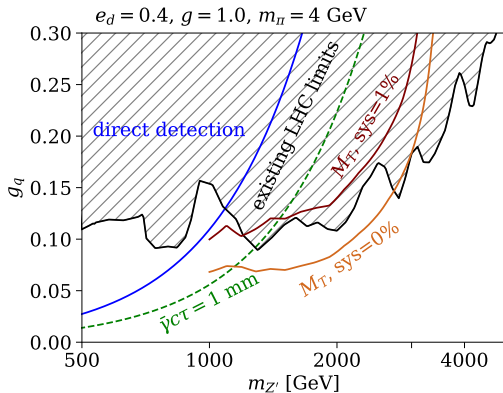


Traditional missing energy searches



- Recast Monojet (ATLAS) and squark/gluino (CMS) searches
- Recasting with CHECKMATE and MADANALYSIS
- Large unconstrained parameter space with displaced ρ^0 decays

Prospective search for semi-visible jets



- Difficult to find with bump hunt in M_T [Cohen et al., 1707.05326]
⇒ More elaborate strategy needed
- LHC complementary to direct detection

- Strongly interacting dark sectors: cosmologically viable and interesting for the LHC
- Freeze-out within dark sector through forbidden annihilations
- At the LHC:
 - Di-jets
 - Traditional missing E_T searches (not optimised)
 - Search for semi-visible jets (see also Colin Fallon's talk)
- Ongoing projects:
 - Displaced ρ^0 decays (unconstrained as of now)
 - Deep learning for dark showers

Backup

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

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}^a F^{\mu\nu,a} + \bar{q}_d i \not{D} q_d - \bar{q}_d M_q q_d \\ & -\frac{1}{4}Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2}m_{Z'}^2 Z'_\mu Z'^\mu - g_q Z'_\mu \sum_{q_{SM}} \bar{q}_{SM} \gamma^\mu q_{SM} ,\end{aligned}$$

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

$$D_\mu q_d = \left(\partial_\mu + ig_D A_\mu + ie_D Z'_\mu Q \right) q_d ,$$

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

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

The pion covariant derivative is given by

$$D_\mu \pi = \partial_\mu \pi + ig [\pi, V_\mu] + ie_d [\pi, Q] Z'_\mu .$$

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

where $\epsilon = \arcsin(2 e_d/g)$.

$$\mathcal{L}_{\text{EFT}} \supset \frac{2 e_d g_q}{g} \frac{m_\rho^2}{m_{Z'}^2} \rho_\mu^0 \sum_{q_{\text{SM}}} \overline{q_{\text{SM}}} \gamma^\mu q_{\text{SM}}. \quad (3)$$

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

- Charged pions stable
- π^0 generically unstable
 - extremely dangerous in early universe (CMB, BBN, relic density, ...)
 - stabilised by G_d -parity if N_F even and $Q \propto \text{diag}(1, -1)$
- ρ^\pm effectively stable if $m_\rho < 2m_\pi$ (tiny three-body decay width)
- ρ^0 - Z' mixing induces ρ^0 decays to $q_{\text{SM}}\bar{q}_{\text{SM}}$

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

Monojet:

- anti- k_T with $R = 0.4$
- $\cancel{E}_T > 250$ GeV
- $p_T > 250$ GeV for the leading jet
- at most four jets with $p_T > 30$ GeV
- $\Delta\phi > 0.4$

CMS squarks and gluinos:

- at least 2 jets are required
- $\cancel{E}_T > 300$ GeV and $H_T > 300$ GeV
- $\Delta\phi(j, \cancel{E}_T) > 0.5$ for the two leading jets
- $\Delta\phi(j, \cancel{E}_T) > 0.3$ for the third and fourth jet
- Each signal region is defined by the combination of an \cancel{E}_T range and an H_T range.

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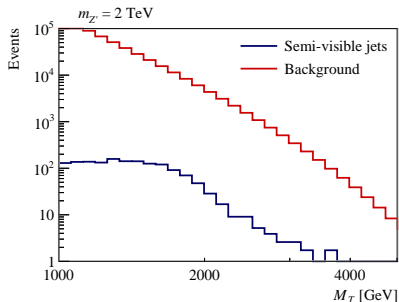
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Prospective search for semi-visible jets

- 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 $M_T = \left(M_{jj}^2 + 2 \left(\sqrt{M_{jj}^2 + p_{Tjj}^2} \cancel{E}_T - \vec{p}_{Tjj} \cdot \vec{\cancel{E}}_T \right) \right)^{1/2}$
- Backgrounds from Cohen et al. [1707.05326]



- $M_T = \left(M_{jj}^2 + 2 \left(\sqrt{M_{jj}^2 + p_{Tjj}^2} \cancel{E}_T \right) - \vec{p}_{Tjj} \cdot \vec{\cancel{E}}_T^{\text{miss}} \right)^{1/2}$
- $\cancel{E}_T > 200$ GeV
- at least two jets with $p_T > 100$ GeV and $|\eta| < 2.4$
- re-clustered with CA algorithm and $R = 1.1$
- $\cancel{E}_T / M_T > 0.15$
- $|\eta_{j_1} - \eta_{j_2}| < 1.1$
- $\Delta\phi < 0.4$ between the missing energy vector and at least one jet