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

Elias Bernreuther

RWTH Aachen University

based on **arXiv:1907.04346**

with Felix Kahlhoefer, Michael Krämer and Patrick Tunney

26 September 2019

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Strongly interacting dark sectors

- Idea: What if the dark sector resembles QCD?
  $\Rightarrow$ DM could be meson/baryon in confining dark sector

- Relic density from interactions within dark sector
  Hochberg et al., 1411.3727
- Possible resolution of DM small-scale problems (SIDM)
  Hochberg et al., 1402.5143

- **Novel collider pheno**:
  - dark showers
  - semi-visible jets — Cohen et al., 1707.05326
  - emerging jets — Schwaller et al., 1502.05409

- **Cosmologically viable and interesting for LHC?**

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**

Dark meson stability

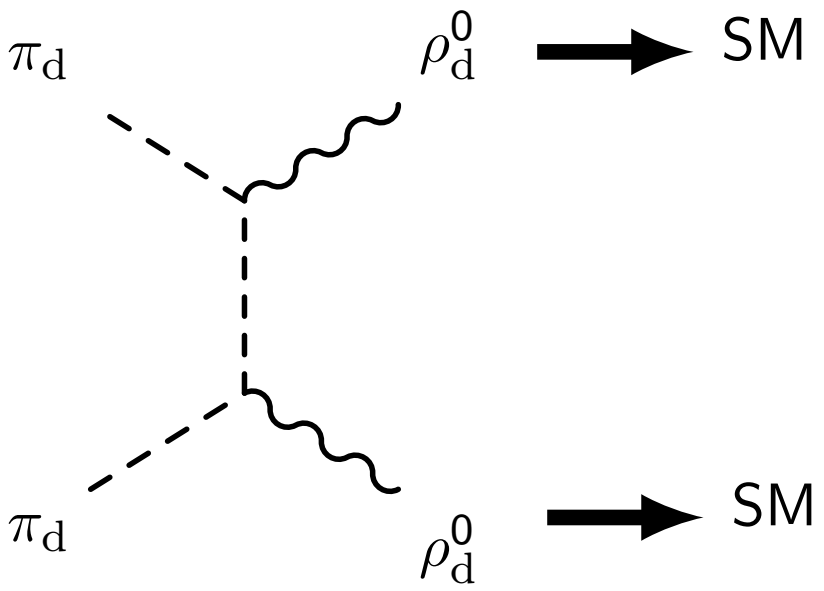
- Charged pion stability protected by $U(1)'$ charge
- $\pi_{\rm d}^0$ generically unstable ($\pi_{\rm d}^0 \to Z'^* Z'^* \to$ SM hadrons)
  - $\to$ dangerous in early universe (relic density, BBN, CMB ...)
  - $\to$ stabilised by G_d-parity if N_F even and $Q \propto \mathrm{diag}(1, -1)$
    Berlin et al., 1801.05805
- $\rho_{\rm d}^{\pm}$ effectively stable if $m_\rho < 2m_\pi$

- $\rho_{\rm d}^0$-Z' **mixing induces** $\rho_{\rm d}^0$ **decays to** $q_{\rm SM}\bar{q}_{\rm SM}$

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

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)

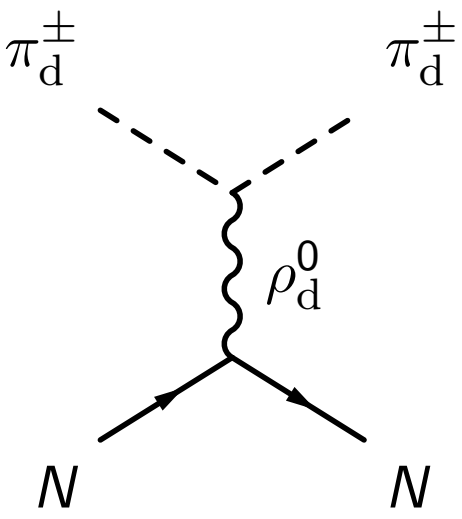


$$\sigma_{\pi\pi\to\rho\rho} \propto \frac{g^2}{m_\pi^2}\, e^{-2\Delta x_f}$$

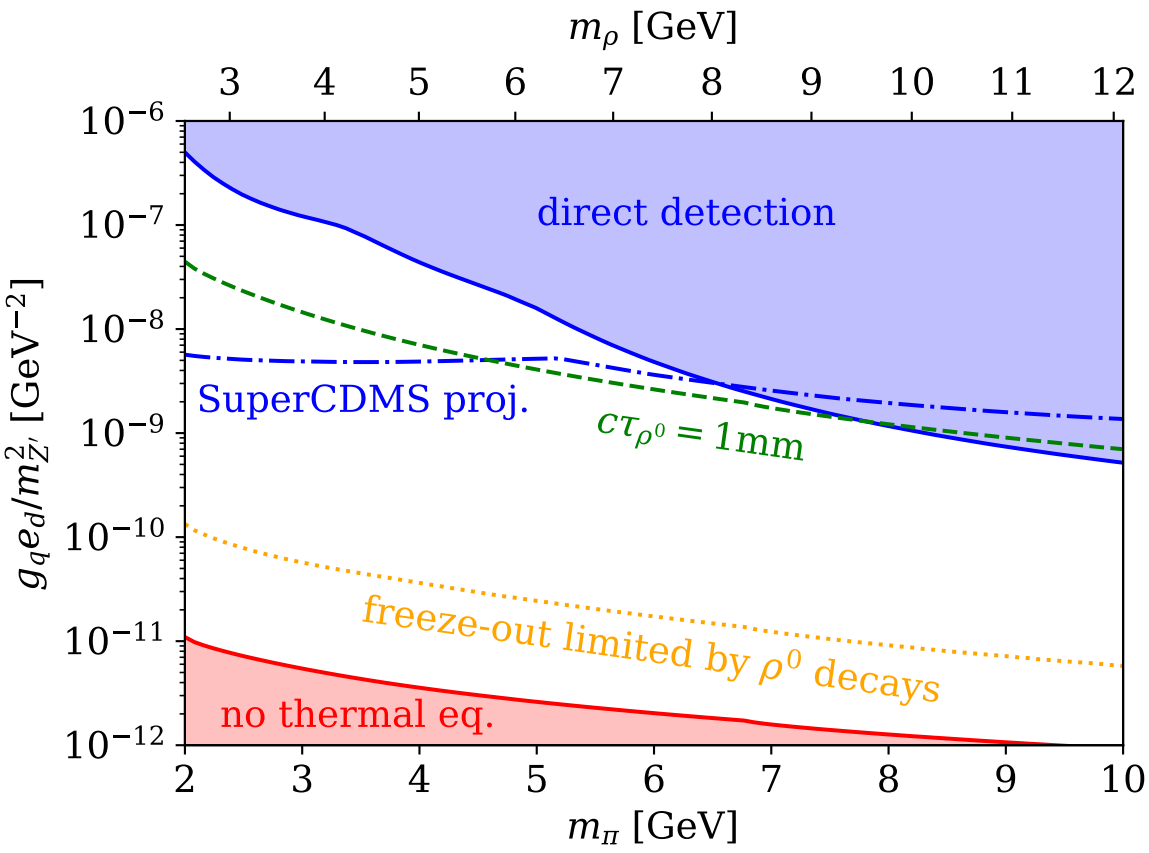
$$\Delta = \frac{m_\rho - m_\pi}{m_\pi} \sim 0.2 \text{ - } 0.5$$

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

Direct detection



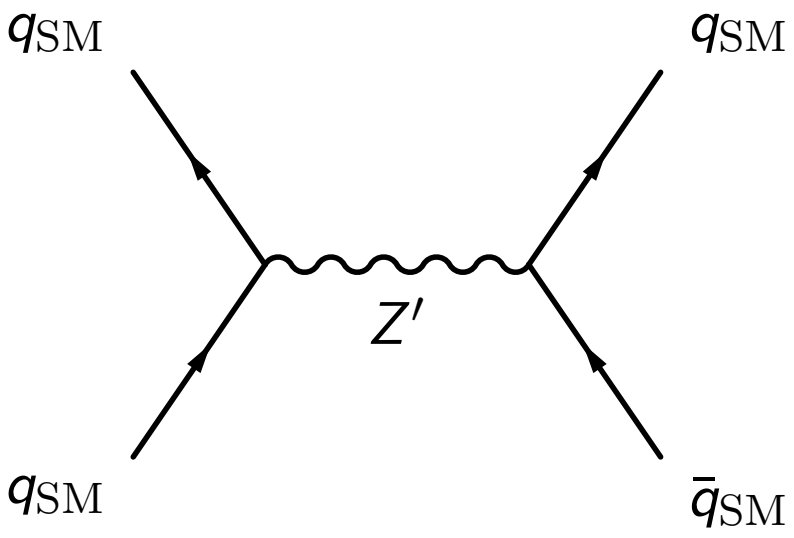
$$\sigma^{\rm SI} \propto \frac{e_d^2 g_q^2}{m_{Z'}^4}$$

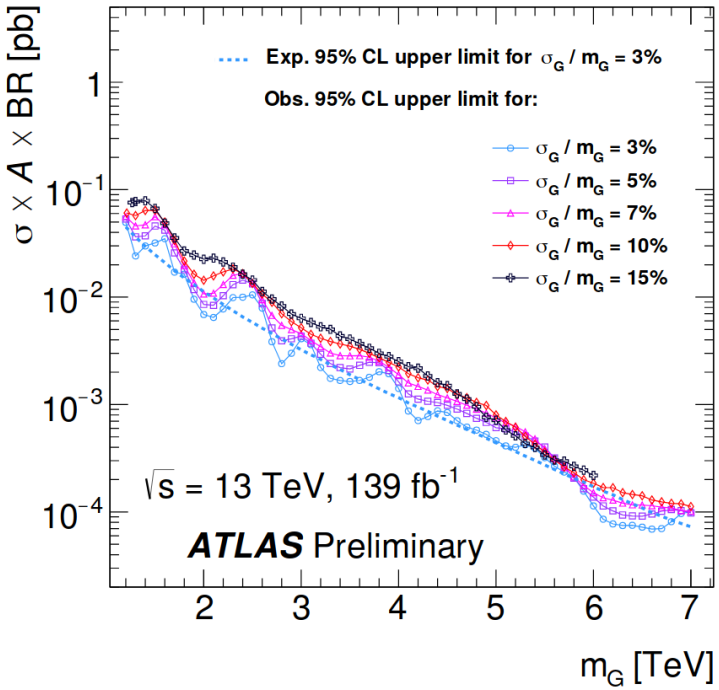


Combination of CRESST-III, CDMSLite, PICO-60, PandaX and XENON1T

Di-jet

- **At LHC resonant Z' production, then . . .**
- Standard possibility: $Z' \to q_{\rm SM}\bar{q}_{\rm SM}$



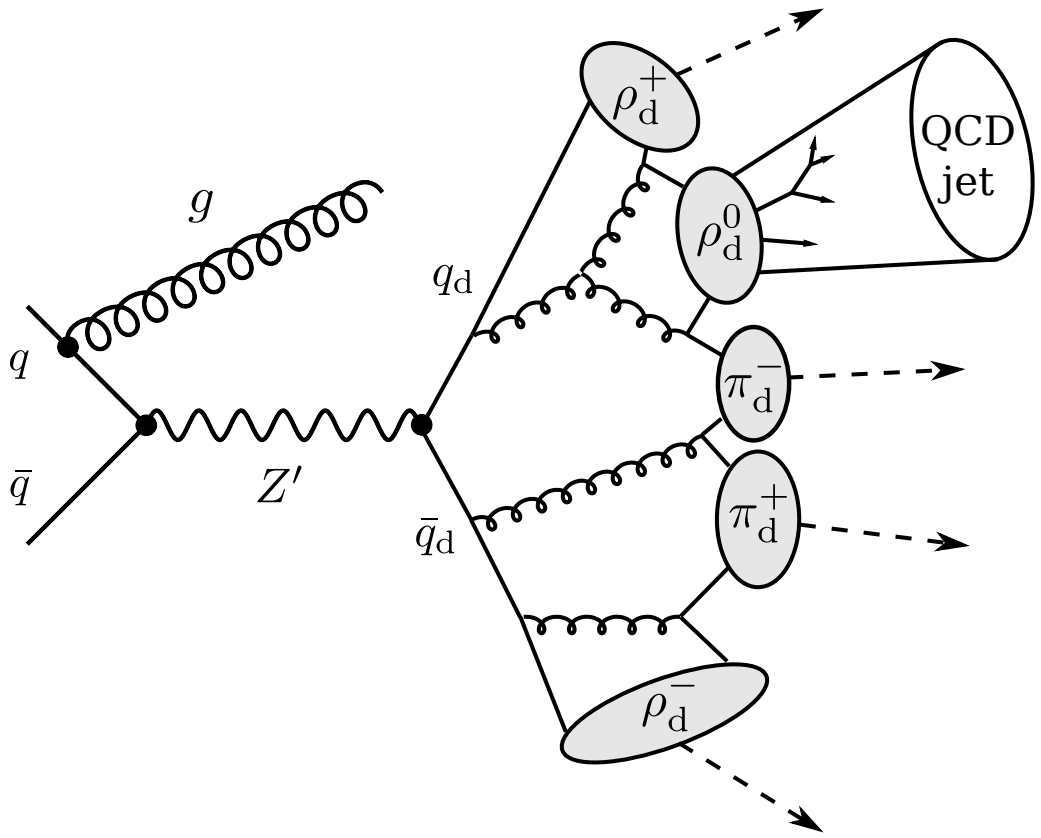


ATLAS-CONF-2019-007

- $\mathrm{BR}\left(Z' \to q_{\rm SM}\bar{q}_{\rm SM}\right) \propto \dfrac{6 \times 3 \times g_q^2}{6 \times 3 \times g_q^2 + 2 \times 3 \times e_d^2}$

Dark showers

- More exciting: production of dark quarks, $pp \to Z' \to q_d \bar{q}_d$
- Shower and hadronisation in dark sector (PYTHIA HIDDEN VALLEY)



- $\mathcal{O}(20)$ dark mesons
- ρ_d^0 decay to SM jets
- Other dark mesons are $\not{E}_T$

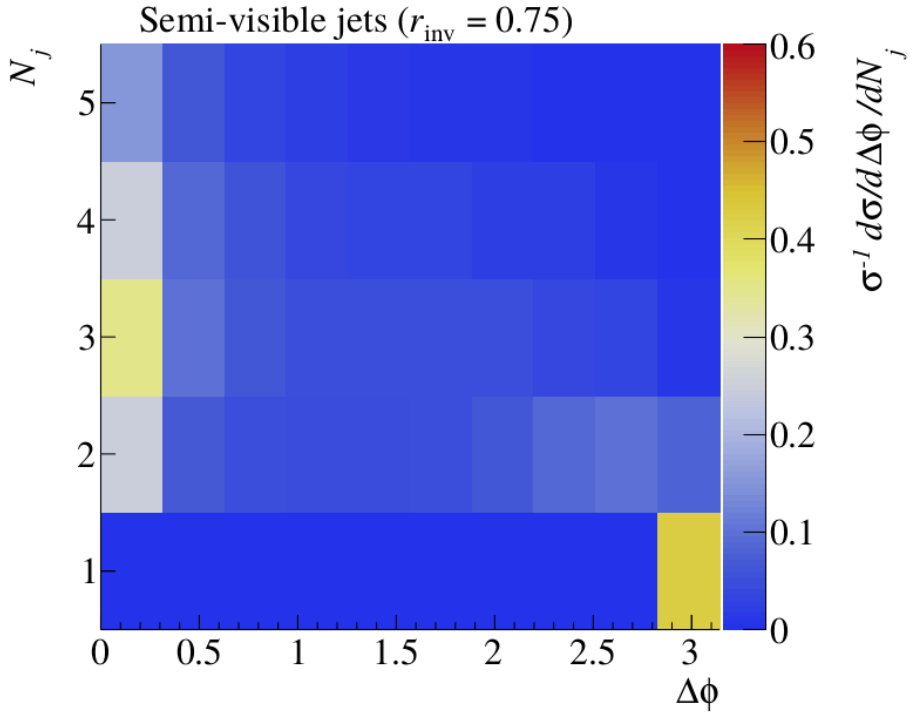
$\Rightarrow$ Semi-visible jets

$r_\mathrm{inv} = 0.75$

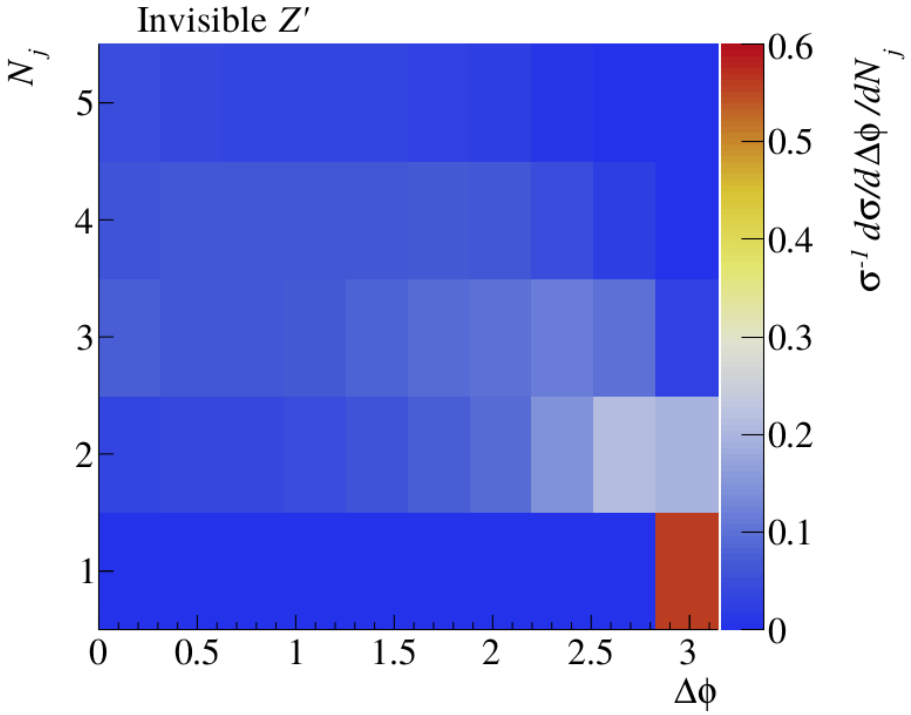
Semi-visible jets

- Signature: jets + $\not{E}_T$
- But missing E_T tends to be **aligned with** the jets
- Characteristic observable: angular separation $\Delta\phi = \min_{i \leq 4} \left\{ \Delta\phi_{j_i, \not{E}_T} \right\}$

Semi-visible jets



Monojet



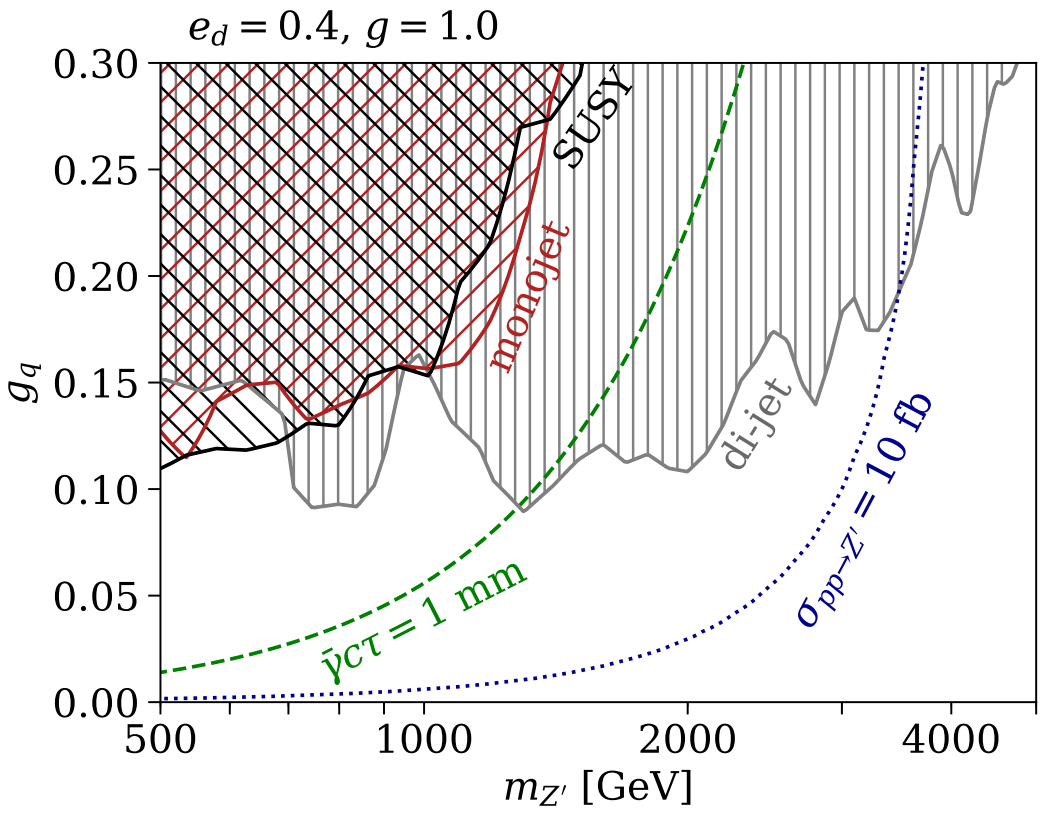
Traditional missing energy searches

To target events with large $\Delta\phi$:

$\Rightarrow$ Recast missing-E_T searches with CheckMATE and MadAnalysis

- ATLAS **monojet search**, 36.1 fb^{-1} (CheckMATE)
  - Invisible dark shower recoils against ISR jet
  - Or partially visible dark showers give energetic jet
- CMS **squark and gluino search**, 35.9 fb^{-1} (MadAnalysis)
  - Two dark showers partially visible
  - Two hemispheres with jets and missing energy in both

Traditional missing energy searches

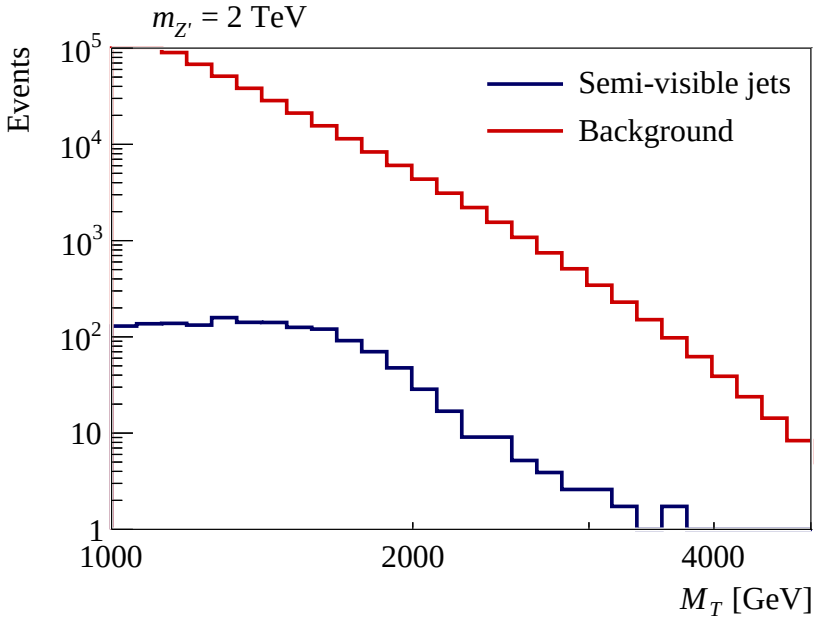


- Missing E_T searches best at low $m_{Z'}$, dijets at large $m_{Z'}$
- Large unconstrained parameter space with displaced ρ^0 decays and sizeable cross section

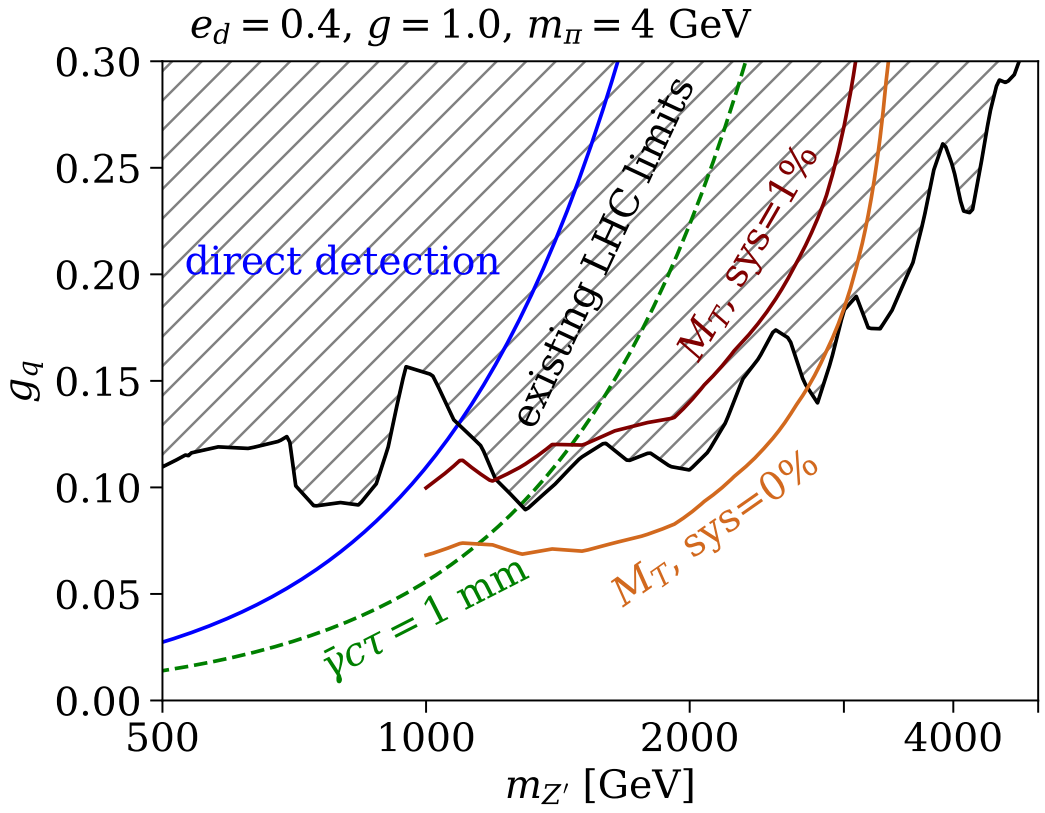
Prospective search for semi-visible jets

To target events where missing E_T is aligned with jets:

- 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 $M_T = \left(M_{jj}^2 + 2\left(\sqrt{M_{jj}^2 + p_{Tjj}^2}\not{E}_T - \vec{p}_{Tjj} \cdot \vec{\not{E}}_T\right)\right)^{1/2}$



Prospective search for semi-visible jets

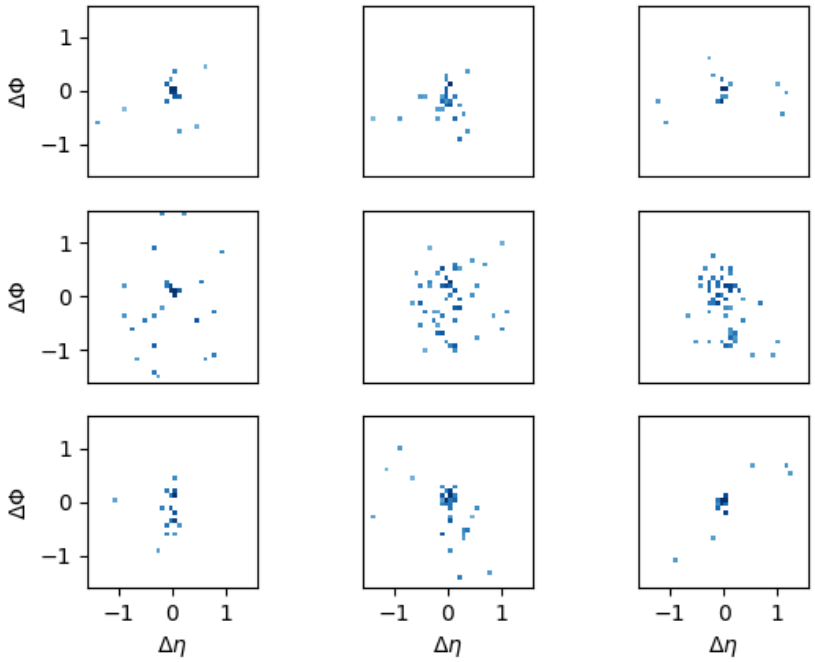


- Difficult to find with bump hunt in M_T
  (variation in dark meson production, systematics)
  $\Rightarrow$ More elaborate strategy needed
- LHC complementary to direct detection

Outlook: machine learning for dark showers

[Thorben Finke]

- M_T search does not use jet substructure information
- Interesting tool: deep learning
- Example for unsupervised approach: autoencoder for jet images
  Heimel et al., 1808.08979; Farina et al., 1808.08992

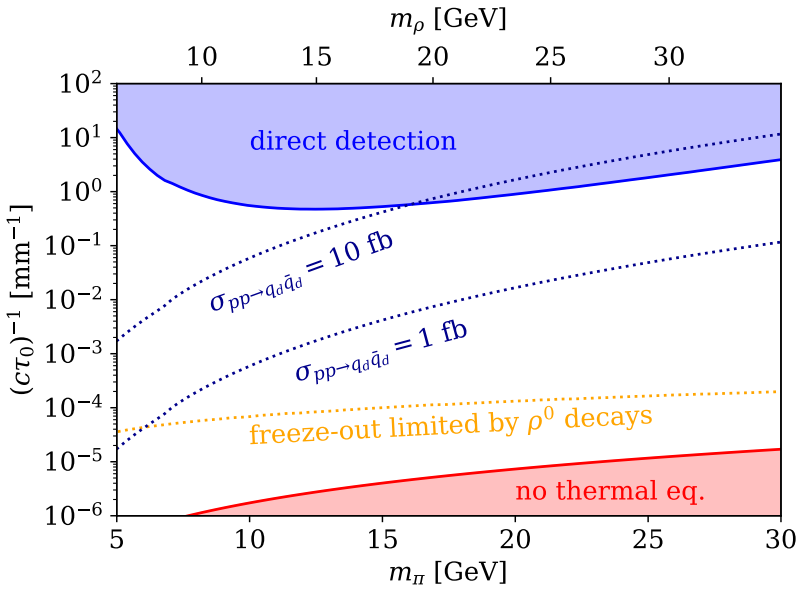


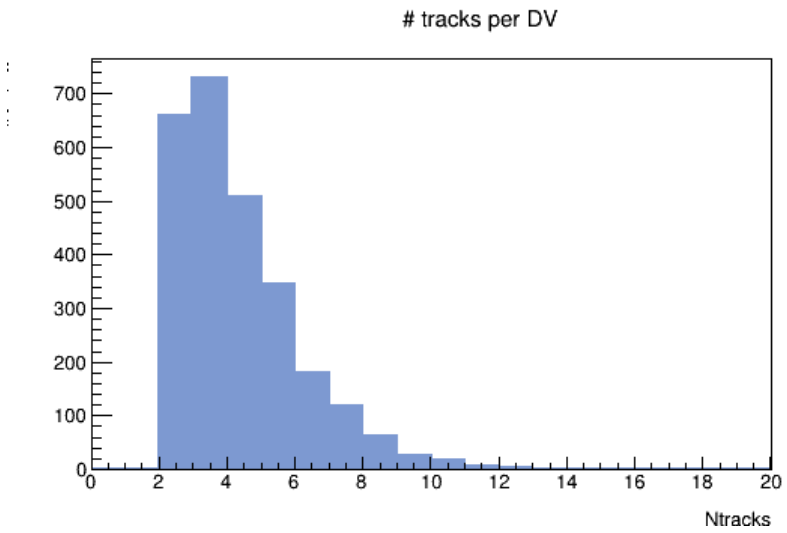
- Challenge: jets qualitatively similar to QCD jets

Outlook: displaced vertices

[Juliana Carrasco]

- $g_q \lesssim 0.1$: displaced vertices from ρ_{d}^0 with detector-size decay lengths





- DV searches require MET and sufficient number of tracks
- Develop dedicated strategy for displaced dark mesons

Conclusions

- 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
  - Prospective search for semi-visible jets
    (more work to be done, CMS search in preparation)
- Ongoing projects:
  - Displaced semi-visible / emerging jets
  - Deep learning for dark showers

Backup

Dark $SU(3)$

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

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

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

$$D_\mu q_{\rm d} = \left(\partial_\mu + ig_D A_\mu + ie_D Z'_\mu Q\right) q_{\rm d}\ ,$$

Chiral EFT

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

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

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

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

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

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

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

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** $q_{\mathrm{SM}}\bar{q}_{\mathrm{SM}}$

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

Search details: missing E_T

Monojet:

- anti-k_T with $R = 0.4$
- $\not{E}_T > 250$ 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
- $\not{E}_T > 300$ GeV and $H_T > 300$ GeV
- $\Delta\phi(j, \not{E}_T) > 0.5$ for the two leading jets
- $\Delta\phi(j, \not{E}_T) > 0.3$ for the third and fourth jet
- Each signal region is defined by the combination of an $\not{E}_T$ range and an H_T range.

Search details: missing E_T

Monojet:

- anti-k_T with $R = 0.4$
- $\not{E}_T > 250$ 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
- $\not{E}_T > 300$ GeV and $H_T > 300$ GeV
- $\Delta\phi(j, \not{E}_T) > 0.5$ for the two leading jets
- $\Delta\phi(j, \not{E}_T) > 0.3$ for the third and fourth jet
- Each signal region is defined by the combination of an $\not{E}_T$ range and an H_T range.

Search details: M_T

- $M_T = \left(M_{jj}^2 + 2 \left(\sqrt{M_{jj}^2 + p_{Tjj}^2} \not{E}_T \right) - \vec{p}_{Tjj} \cdot \vec{\not{E}}_T^{\text{miss}} \right)^{1/2}$
- $\not{E}_T > 200$ GeV
- at least two jets with $p_T > 100$ GeV and $|\eta| < 2.4$
- re-clustered with CA algorithm and $R = 1.1$
- $\not{E}_T / M_T > 0.15$
- $|\eta_{j_1} - \eta_{j_2}| < 1.1$
- $\Delta\phi < 0.4$ between the missing energy vector and at least one jet