Karlsruher Institut für Technologie

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Strongly interacting dark sectors with light vector mesons

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Based on work done in collaboration with Felix Kahlhoefer (KIT), Suchita Kulkarni (Graz University) and Elias Bernreuther (FermiLab)

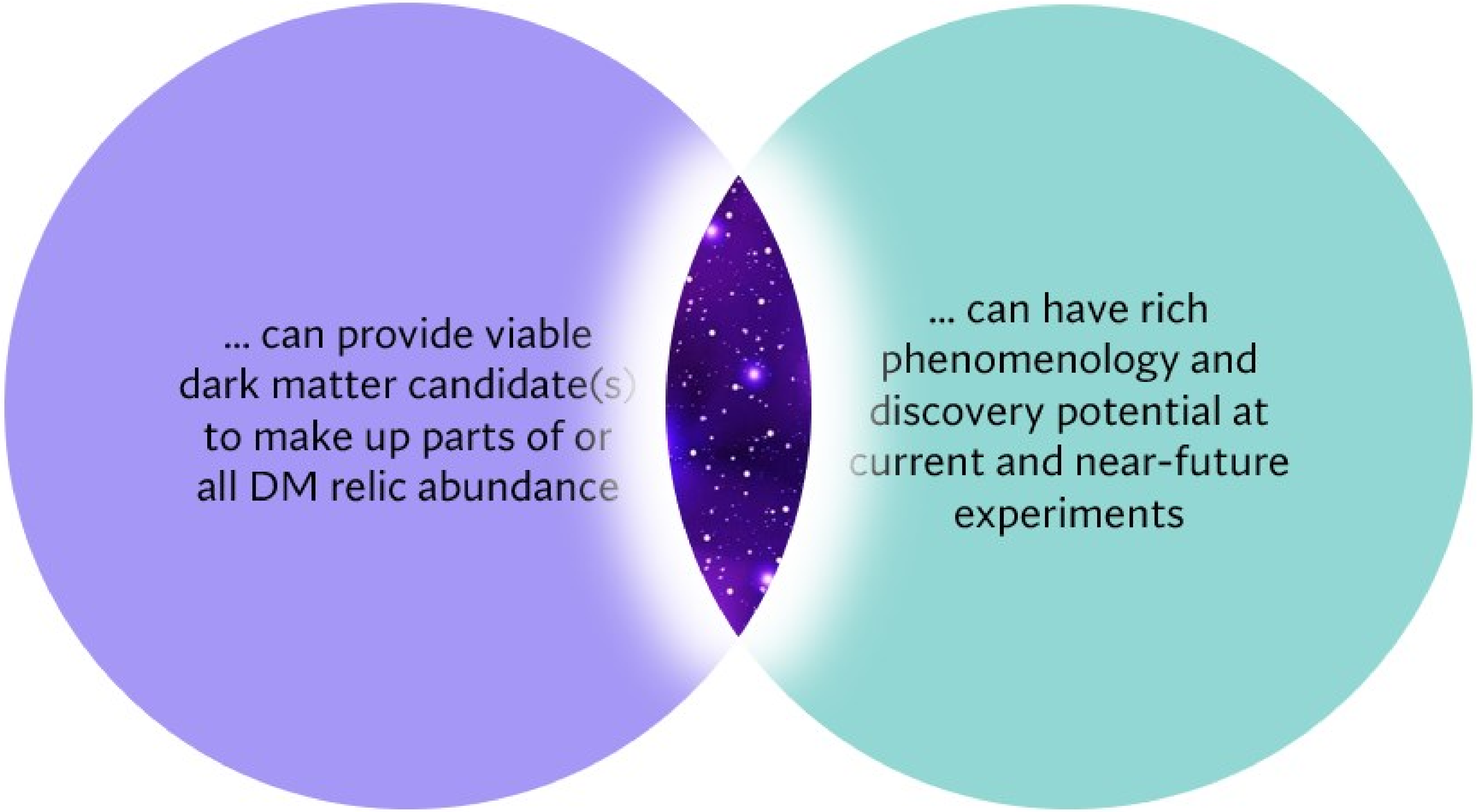
15th International Workshop on the Identification of Dark Matter, July 9th 2024 – L’Aquila, Italy

Strongly interacting dark sectors ...

... can provide viable dark matter candidate(s) to make up parts of or all DM relic abundance

... can have rich phenomenology and discovery potential at current and near-future experiments

Strongly interacting dark sectors ...



SU(N_{CD}) dark sector theory

Confinement / breakdown of UV theory

$$\mathcal{L}_{Ch} \supset \frac{f_{\pi_D}^2}{4}\mathrm{Tr}\big(D_\mu U D^\mu U\big) + \left[\frac{\mu_D^3}{2}\mathrm{Tr}\big(\mathrm{M}_q U^\dagger\big) + \mathrm{h.c.}\right]$$

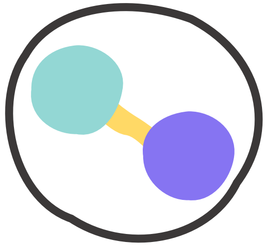
$E \sim \Lambda_D$

$$\mathcal{L}_{UV} = -\frac{1}{4}G^a_{D\mu\nu}G_D^{a\mu\nu} + \bar{q}_d(i\gamma^u D_\mu - M_q)q_D$$

Energy

Particles of the theory

Bound states made up of dark quarks and gluons



Particles of the theory

Dark quarks (N_{f_D} number of flavors)

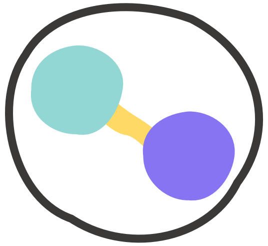
Dark gluons

Dark bound states

Consider the lightest bound state – **the dark pion**

- Pseudo-Goldstone boson of chiral symmetry breaking
- Can be stable – **dark matter candidate**

π_D
Pseudo-scalar



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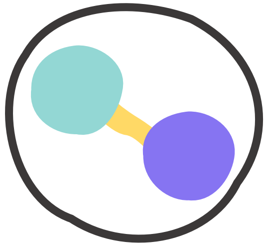

Dark pions can freeze out via $3\pi_D \rightarrow 2\pi_D$ interactions – **the SIMP miracle**

See Y. Hochberg, E. Kuflik, T. Volansky, and J. G. Wacker, Phys. Rev. Lett. 113, 171301, [1402.5143]

- Interactions induced by Wess-Zumino-Witten (WZW) anomaly term
- Relic abundance ($\Omega_D h^2 \lesssim 0.12$) achievable for sub-GeV dark pions
- Coupling to SM can yield detectable signals

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To satisfy relic abundance the dark pion must have large self-interactions that violate constraints from the Bullet Cluster!

https://www.esa.int/ESA_Multimedia/Images/2007/07/The_Bullet_Cluster2

Self-interaction cross section:

$$\sigma_{SI} \propto \frac{\xi^4}{m_\pi^2} \leq \text{BC limit}$$

to satisfy BC use higher mass

General SIMP cross section:

$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{\alpha_{\text{eff}}}{m_{\pi_D}^5}$$

higher mass $\rightarrow$ less efficient FO
$\rightarrow$ too large relic abundance

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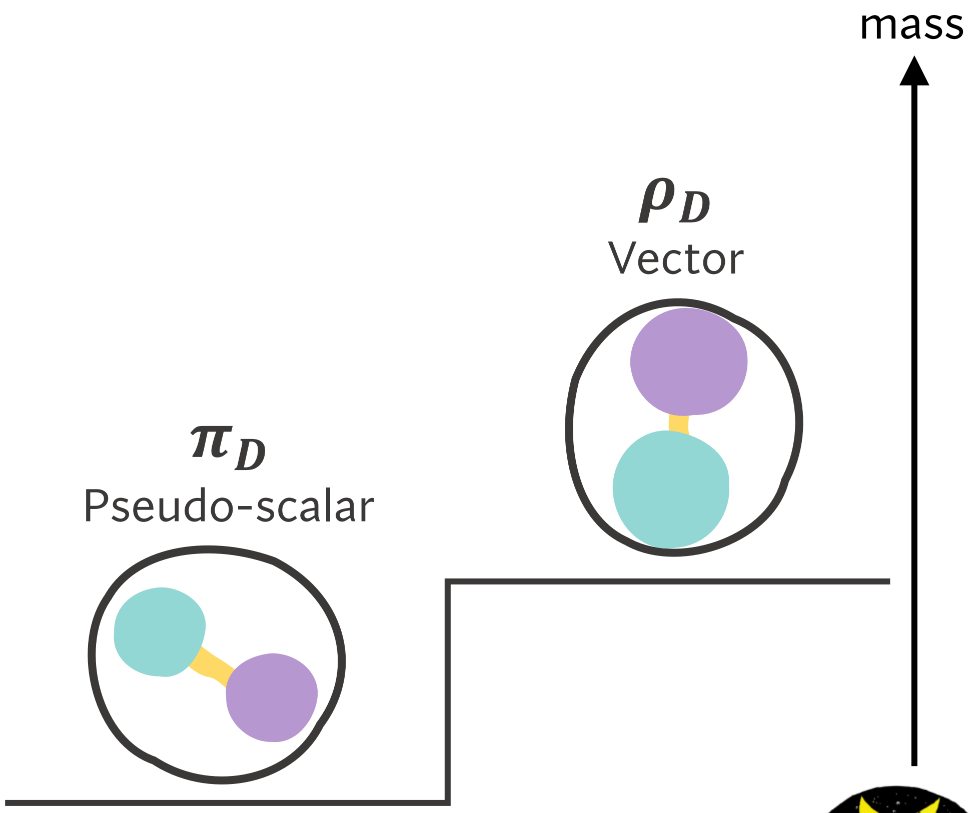
Dark bound states

Consider now also the second-lightest bound state – **the dark rho meson**

- Usually unstable, decays to DS or SM



Dark bound states

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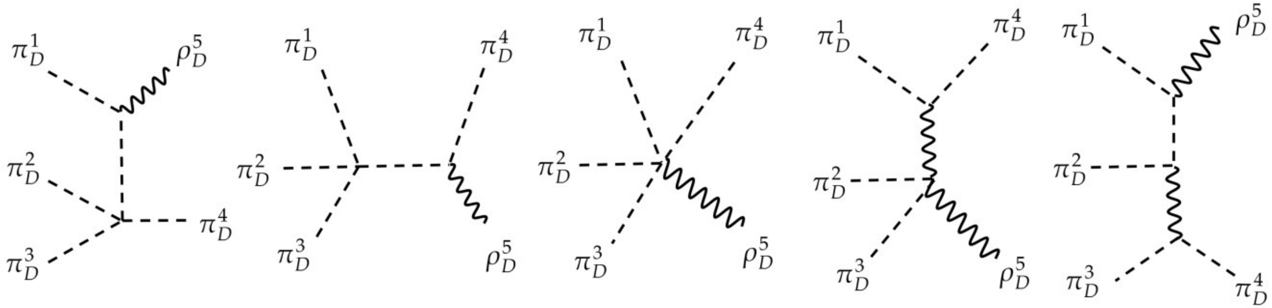
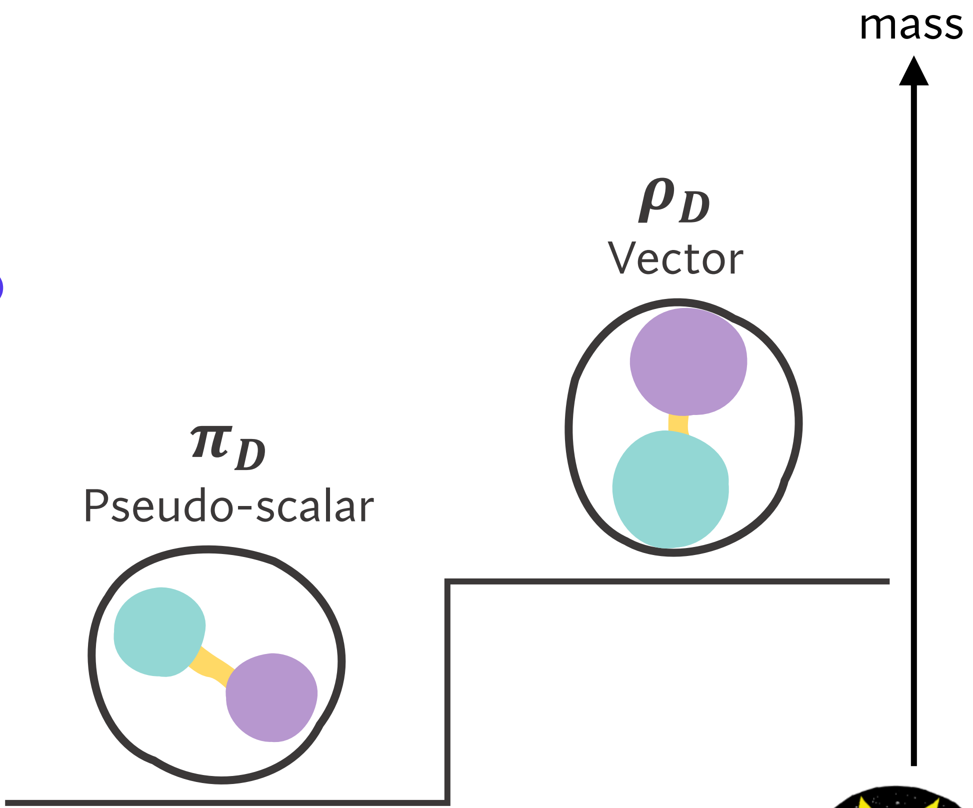
- Usually unstable, decays to DS or SM

If $m_{\rho_D} < 2m_{\pi_D}$ the channel $\boldsymbol{3\pi_D \to \pi_D \rho_D}$ opens up

See E. Bernreuther, NH, F. Kahlhoefer, S. Kulkarni [2311.17157]

- Favorable velocity dependence (s-wave), over the $3\pi_D \to 2\pi_D$ (d-wave)
- ρ_D is forced to decay to SM





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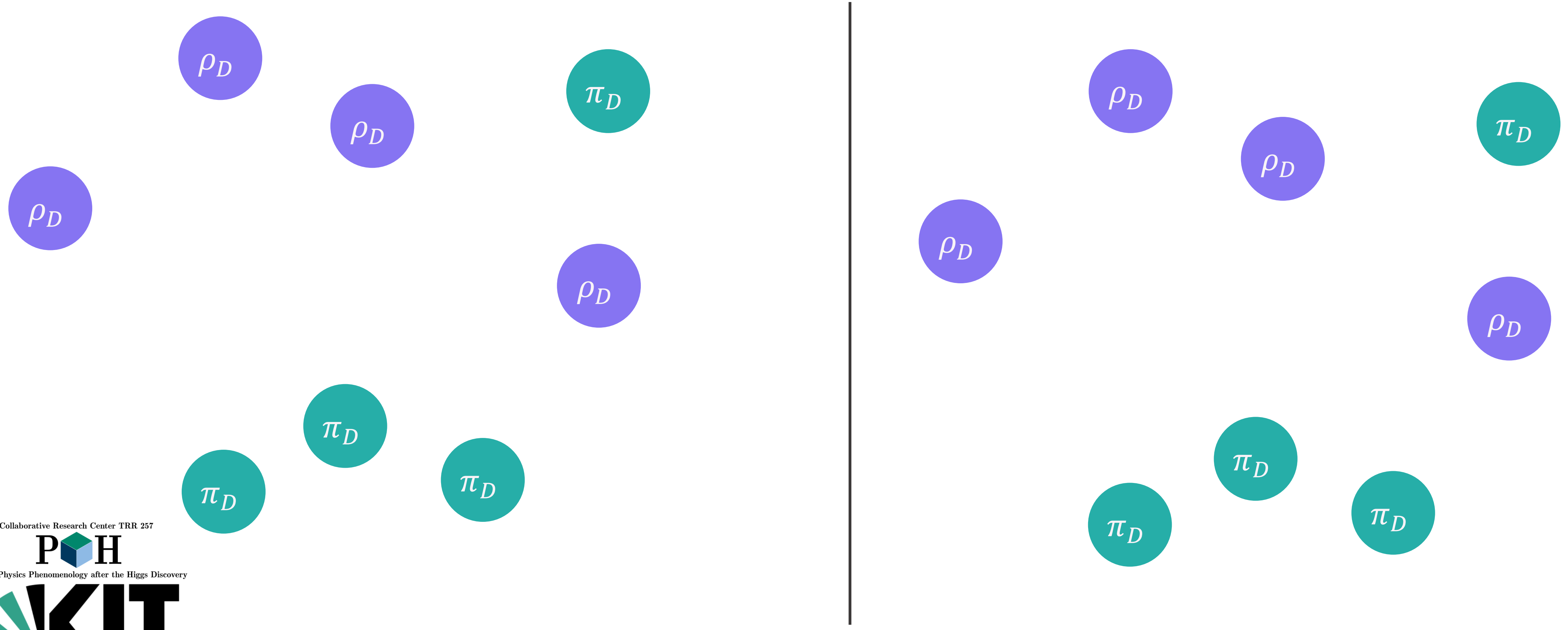
Relic abundance

Early (hot) Universe

High energy is enough to produce many new particles

Universe with **heavy** ρ_D | Universe with **light** ρ_D

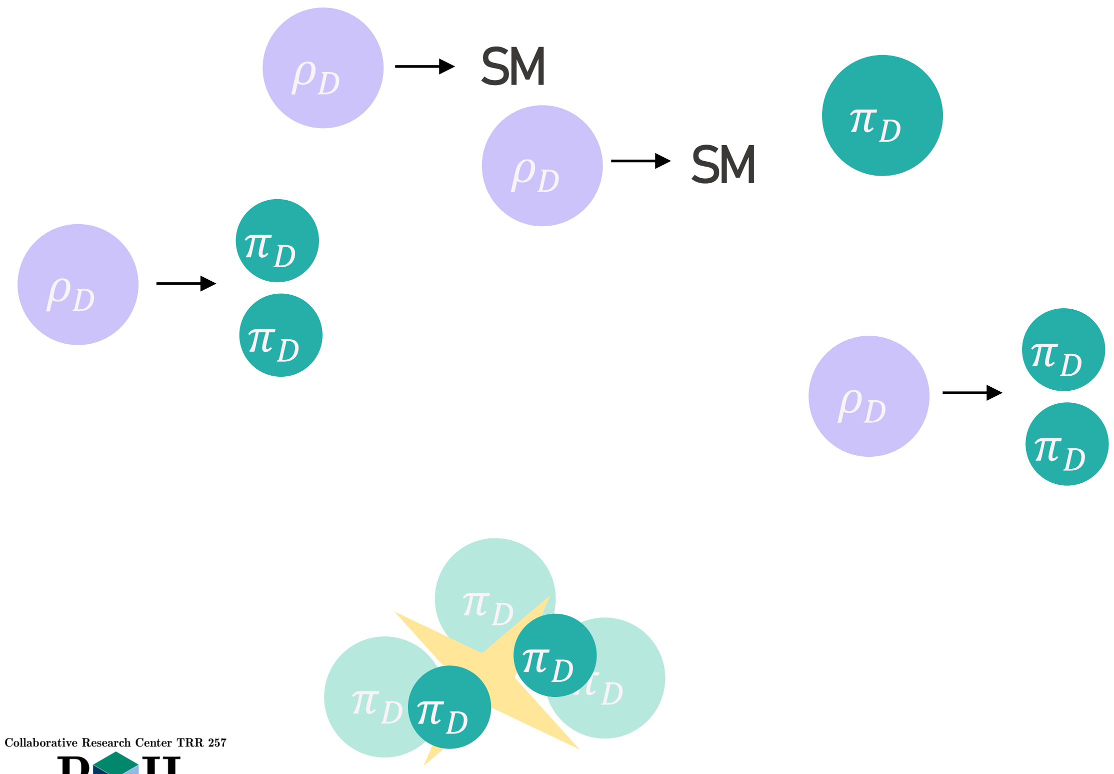


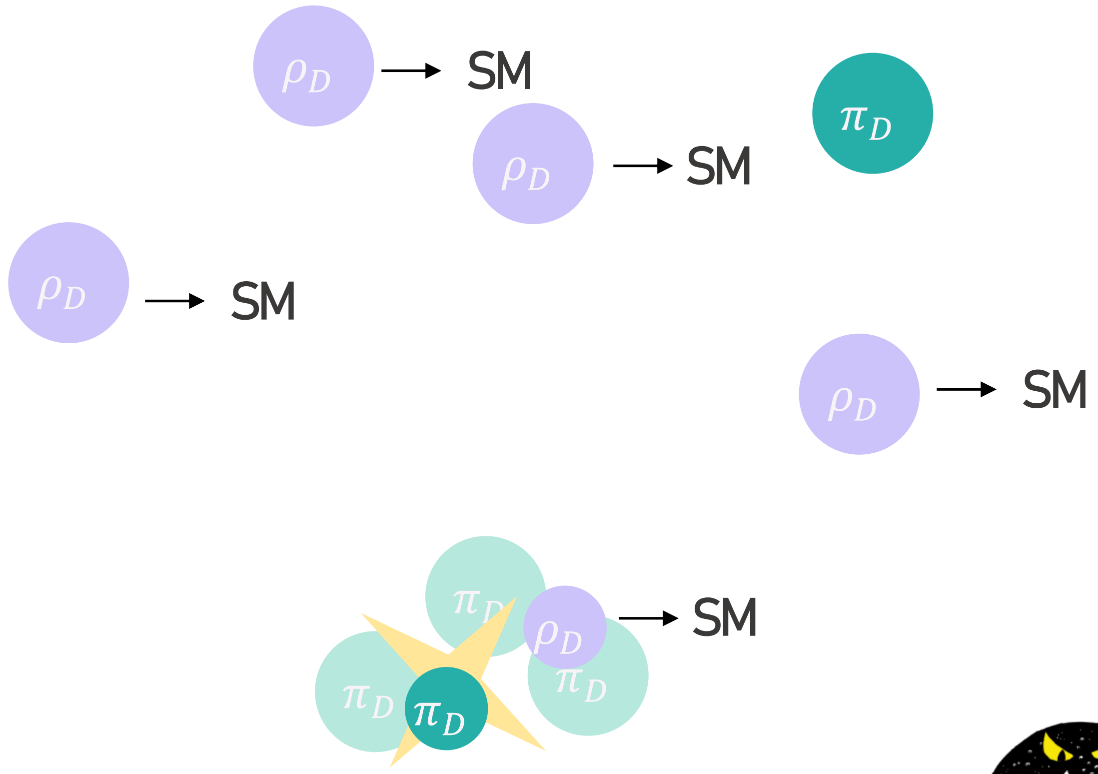
Relic abundance

Freeze-out point
Energy falls below threshold to produce more of these particles while some decay or annihilate

Universe with **heavy** ρ_D

Universe with **light** ρ_D





Relic abundance

Relic abundance reached

Universe with **heavy** ρ_D | Universe with **light** ρ_D

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Relic abundance

To calculate the relic abundance we must first discuss the parameters

E. Bernreuther, NH, F. Kahlhoefer, S. Kulkarni [2311.17157]

We need to specify $\mathbf{N_{c_D}}$ and $\mathbf{N_{f_D}}$

- These parameters are discrete
- Our range of interest is limited to $\mathbf{N_{c_D}}$, $\mathbf{N_{f_D}} \in [2,3,4]$ (due to simulation tool (PYTHIA) and ~ SM QCD)

→ Not a problem!

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Then, a QCD-like strongly interacting dark sector will have 2 free parameters:

- A mass scale, m_{q_D} (UV) or m_{π_D} (mass-degenerate quarks)
- A mass ratio, $\frac{m_{q_D}}{\Lambda_D}$ (UV) or $\frac{m_{\pi_D}}{f_{\pi_D}}$

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We can determine the meson mass spectrum (i.e. m_{ρ_D}) via **lattice simulations** (non-perturbative) and obtain the relation:

Using results from *P. Maris and P. C. Tandy, Nucl. Phys. B Proc. Suppl. 161 (2006), 136–152*

$$\xi \equiv \frac{m_{\pi_D}}{f_{\pi_D}} = 7.79\,\frac{m_{\pi_D}}{m_{\rho_D}} + 0.57\left(\frac{m_{\pi_D}}{m_{\rho_D}}\right)^2$$

! We explore the range $1.45 < \frac{m_{\rho_D}}{m_{\pi_D}} < 2$, corresponding to $4 \lesssim \xi \lesssim 5.7$
(safe from perturbativity limit at $\xi \sim 4\pi$)

Relic abundance

We must then solve the Boltzmann equation

E. Bernreuther, NH, F. Kahlhoefer, S. Kulkarni [2311.17157]

$$\dot{n}_{\pi_D} + 3Hn_{\pi_D} = \langle \sigma v^2 \rangle_{3\pi_D \to \pi_D \rho_D} n_{\pi_D} \left(\left(n_{\pi_D}^{eq}\right)^2 - n_{\pi_D}^2 \right)$$

$$\langle \sigma v^2 \rangle_{3\pi_D \to \pi_D \rho_D} = \frac{|M|^2_{3\pi_D \to \pi_D \rho_D}}{144\pi S_\alpha S_\beta m_{\pi_D}^3} \sqrt{4 - 5y + y^2} \quad \left(\text{with } y = \frac{m_{\rho_D}^2}{4m_{\pi_D}^2}\right)$$

$$|\mathcal{M}|^2_{3\pi_D \to \pi_D \rho_D} = \frac{8m_{\pi_D}^4 (1-y)(4-y)\left(\frac{\Gamma_{\text{th}}^2}{m_{\pi_D}^2} + 4y^2\right)\left(5N_{f_D}^4 \frac{\Gamma_{\text{th}}^2}{m_{\pi_D}^2}(13y+2)^2 + 32(2Ay^2 + 2By + C)\right)}{3f_{\pi_D}^6 \left(\frac{\Gamma_{\text{th}}^2}{m_{\pi_D}^2} + 64\right)(2y+1)^2 \left(9\frac{\Gamma_{\text{th}}^2}{m_{\pi_D}^2} + 64(1-y)^2\right)}$$

$$A = \frac{(821N_{f_D}^4 - 168N_{f_D}^2 + 36)}{N_{f_D}(N_{f_D}^2 - 1)^2}, \qquad B = \frac{(245N_{f_D}^4 - 114N_{f_D}^2 + 36)}{N_{f_D}(N_{f_D}^2 - 1)^2}, \qquad C = \frac{(37N_{f_D}^4 - 30N_{f_D}^2 + 18)}{N_{f_D}(N_{f_D}^2 - 1)^2}$$

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Classic SIMP-scenario:

$$\langle\sigma v^2\rangle_{3\pi_D\to 2\pi_D} = \frac{5\sqrt{5}N_{C_D}^2\xi^{10}}{4608\pi^5 m_{\pi_D}^5 x^2 N_{f_D}}$$

Ratio:

$$R \equiv \frac{\langle\sigma v^2\rangle_{3\pi_D\to\pi_D\rho_D}}{\langle\sigma v^2\rangle_{3\pi_D\to 2\pi_D}} = \frac{\alpha^{\text{eff}}_{3\pi_D\to\pi_D\rho_D}}{\alpha^{\text{eff}}_{3\pi_D\to 2\pi_D}}$$

$$\approx (1800-8500)\times\frac{1}{N_{f_D}^2\xi^4}\frac{x^2}{\sqrt{1-y}}$$

R >1 for relevant space
R↑ as y→1 ($m_{\rho_D}\to 2m_{\pi_D}$)
R↑ as x↑ (universe cools)

$$|\mathcal{M}|^2_{3\pi_D\to\pi_D\rho_D} = \frac{8m_{\pi_D}^4(1-y)(4-y)(\frac{\Gamma_{\text{th}}^2}{m_{\pi_D}^2}+4y^2)(5N_{f_D}^4\frac{\Gamma_{\text{th}}^2}{m_{\pi_D}^2}(13y+2)^2+32(2Ay^2+2By+C))}{3f_{\pi_D}^6(\frac{\Gamma_{\text{th}}^2}{m_{\pi_D}^2}+64)(2y+1)^2(9\frac{\Gamma_{\text{th}}^2}{m_{\pi_D}^2}+64(1-y)^2))}$$

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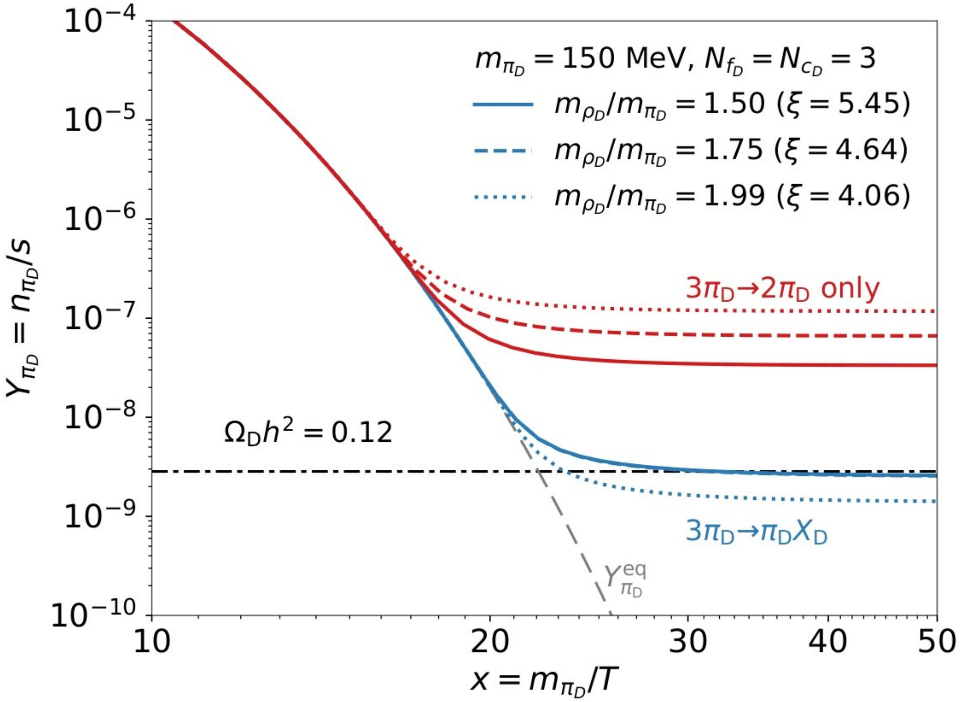
Relic abundance

Results – Freeze-out of π_D

E. Bernreuther, NH, F. Kahlhoefer, S. Kulkarni [2311.17157]



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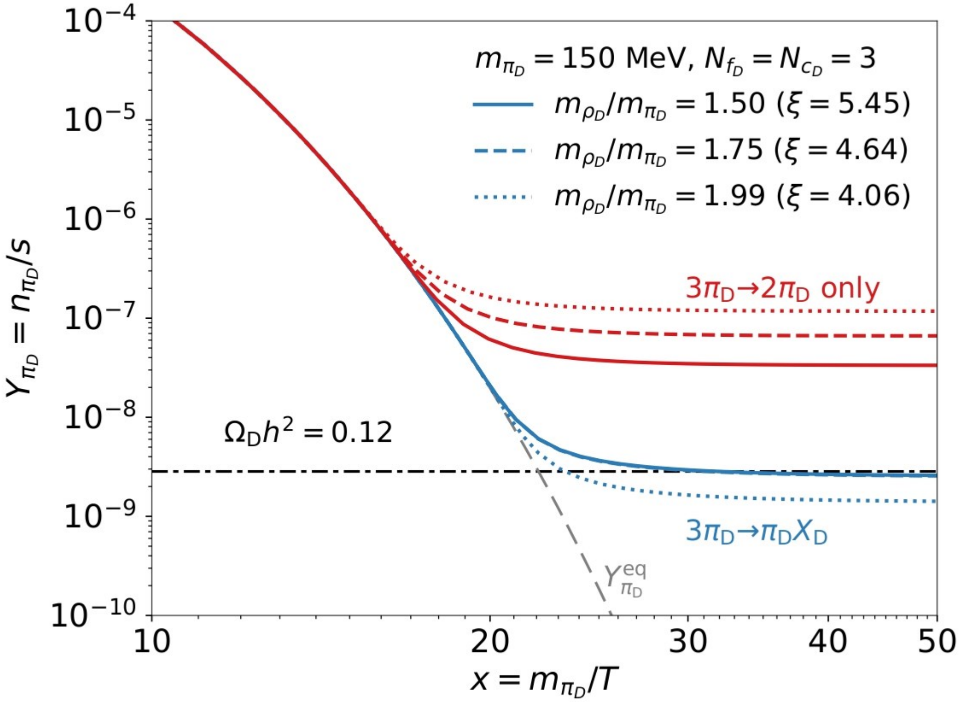
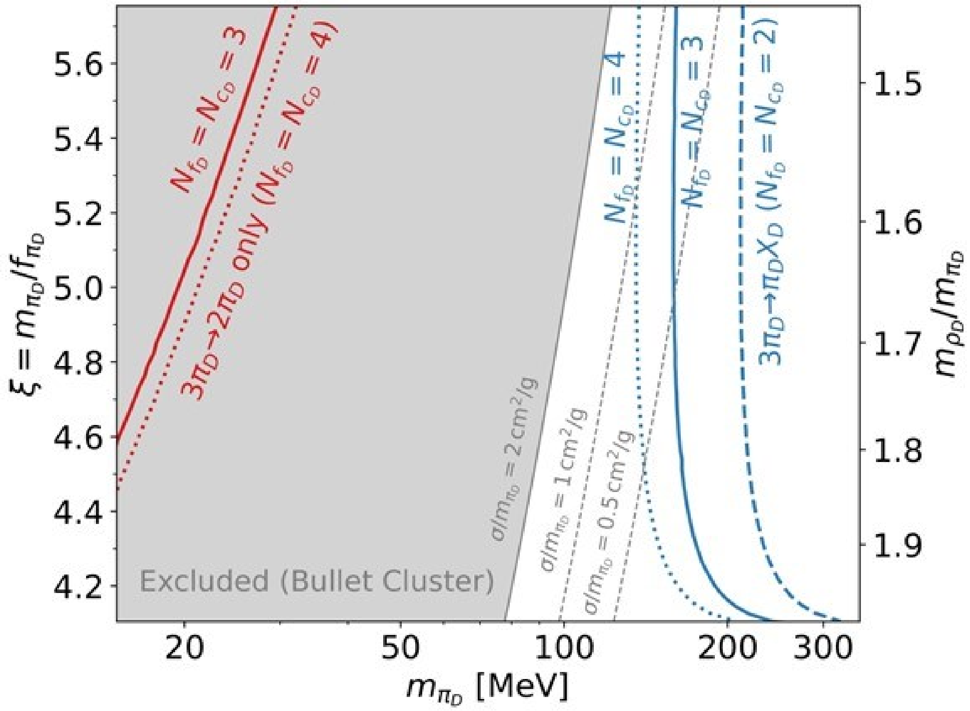


- For $m_{\pi_D} \sim 150$ MeV:
  - $3\pi_D \nrightarrow \pi_D \rho_D$: DM overproduced (need lower mass)
  - $3\pi_D \rightarrow \pi_D \rho_D$: DM produced at correct relic abundance
- We can go to higher masses without overproducing DM
  → Does this solve tension with BC constraints?

Relic abundance

Results – Comparison to BC constraints

E. Bernreuther, NH, F. Kahlhoefer, S. Kulkarni [2311.17157]



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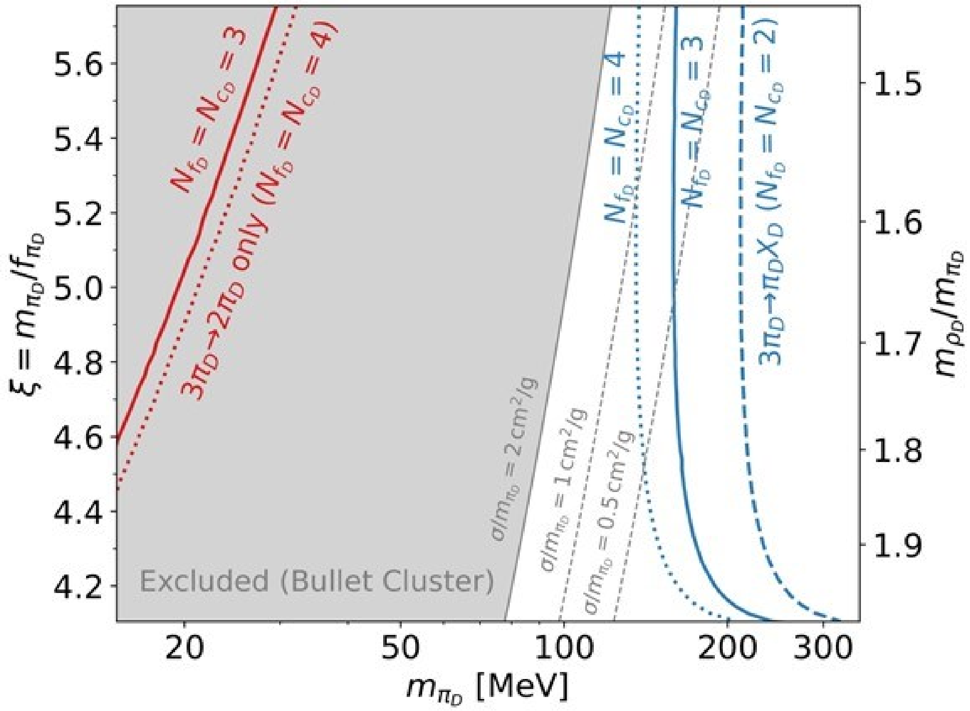


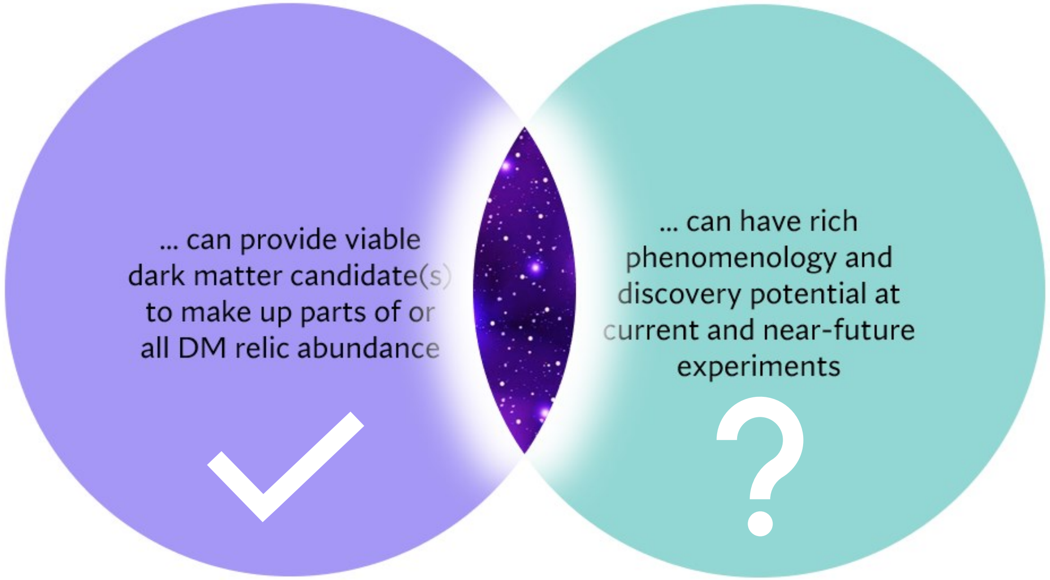
- Light vector mesons enhance the dark pion depletion, helping us to avoid SI constraints from BC

  → Yes, we found one way to solve this tension and so far the parameter space of this model is wide open

- Enhancement of cross section as $m_{\rho_D} \to 2m_{\pi_D}$ (as expected)

- Note no N_{f_D}=2 model for classic SIMP (WZW 5-pnt interaction only exists for N_{f_D}>2)

Phenomenology (dark showers)



Generally, the ρ_D will mix with the SM photon, and/or we can add a portal* between the SM and DS

*Popular choice: **Z' boson**

- The gauge boson of a U(1)' symmetry (dark photon)
- Will assign "dark charges" and give $\pi_D^{\pm}$ (stabilization)
- Potential of Z' detection by bump-hunt

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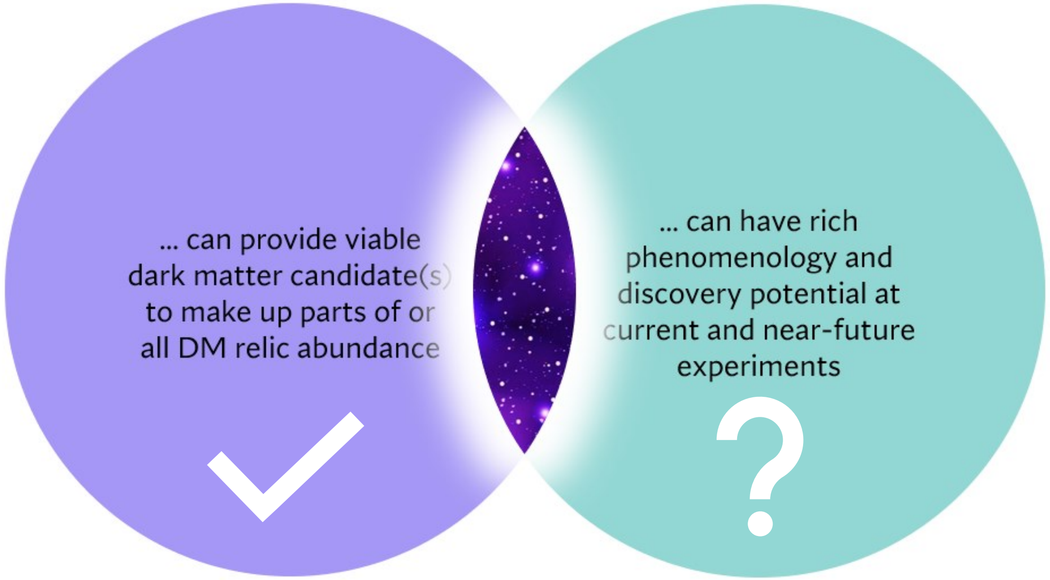

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Dark showers and signatures

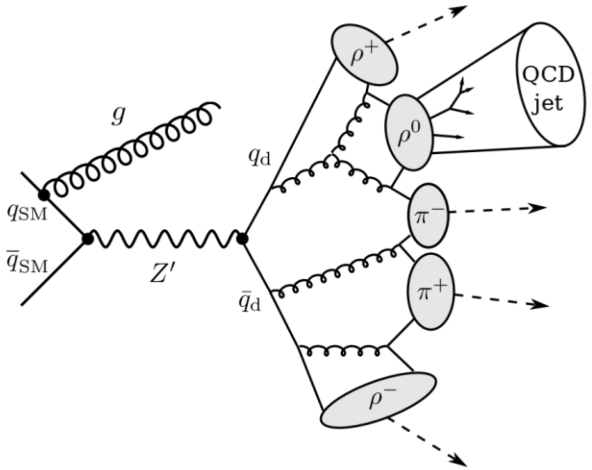

Figure: E. Bernreuther, F. Kahlhoefer, M. Krämer, P. Tunney [1907.04345]

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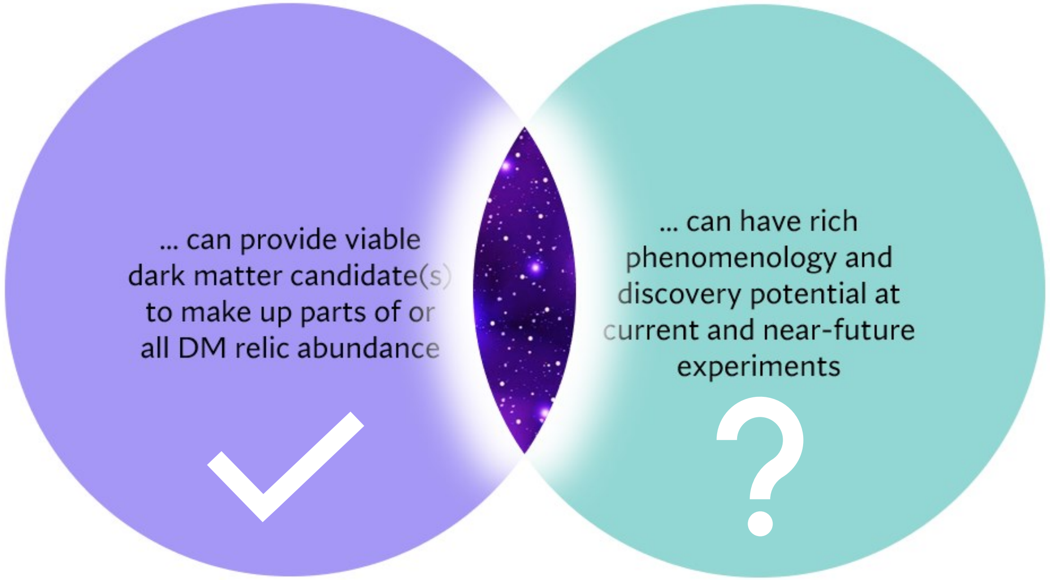

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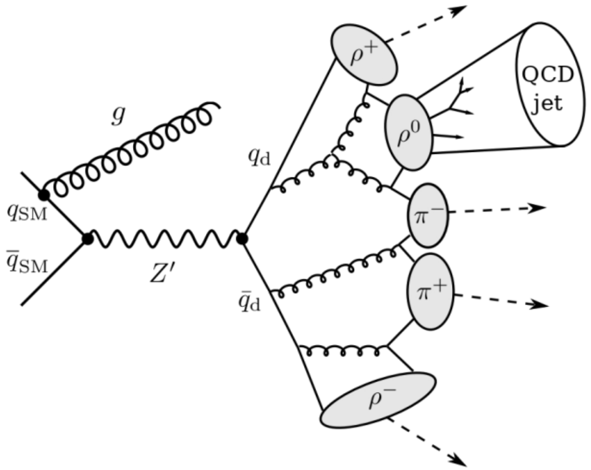

Figure: E. Bernreuther, F. Kahlhoefer, M. Krämer, P. Tunney [1907.04345]

- Long-lived ρ_D can yield **displaced vertices** (BaBar, Belle II, SHiP, FASER, NA64)

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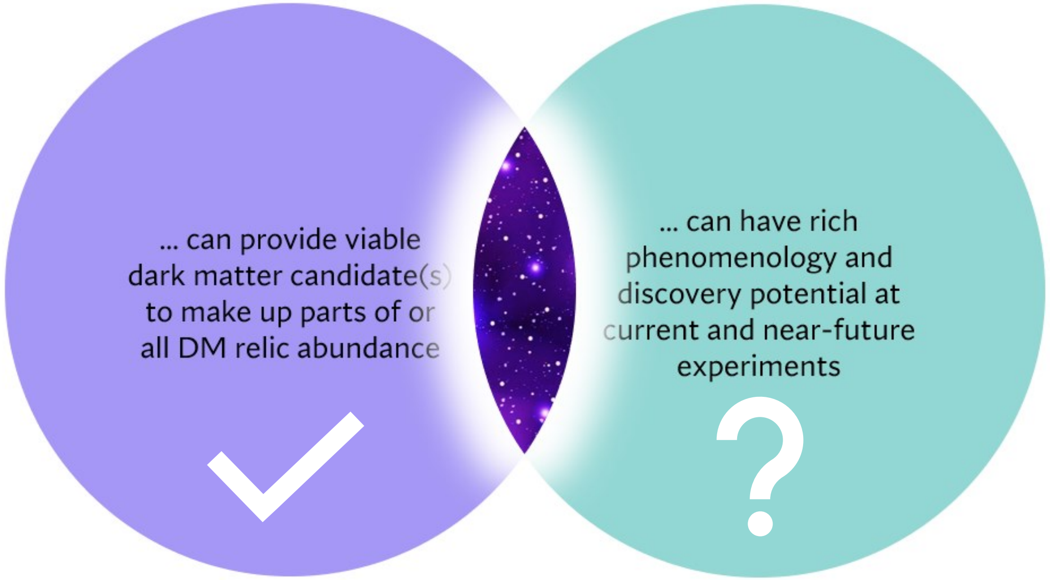

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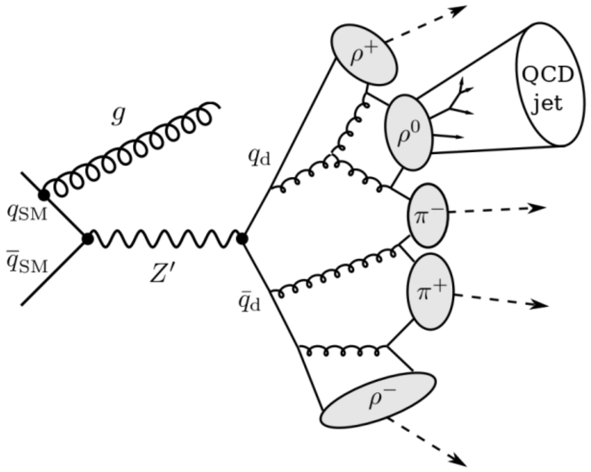


Figure: E. Bernreuther, F. Kahlhoefer, M. Krämer, P. Tunney [1907.04345]

- Long-lived ρ_D can yield **displaced vertices** (BaBar, Belle II, SHiP, FASER, NA64)
- Prompt decays can still yield distinct signatures if there is a mix of stable (invisible) and unstable SM-decaying (visible) particles: **semi-visible jets** (LHCb, CMS, ATLAS)

Conclusion

I introduced a strongly interacting dark sector with $m_{\rho_D} < 2m_{\pi_D}$

- The $3\pi_D \to \pi_D \rho_D$ process dominates freeze-out and enhances DM depletion
- The π_D is the DM candidate and can explain DM with m_{π_D}~150-250 MeV
- The ρ_D will decay to SM particles and may leave distinct signatures in collider experiments

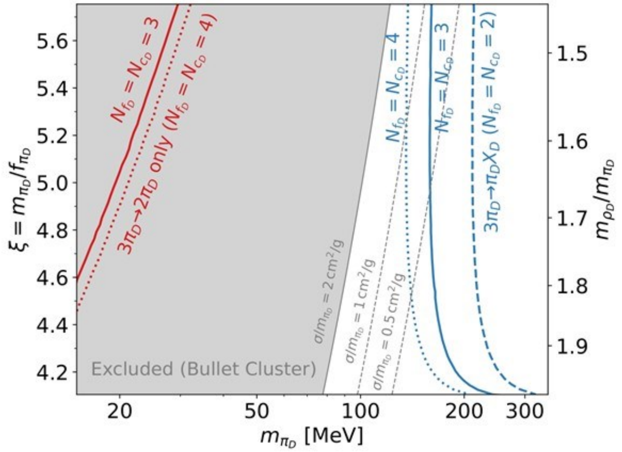
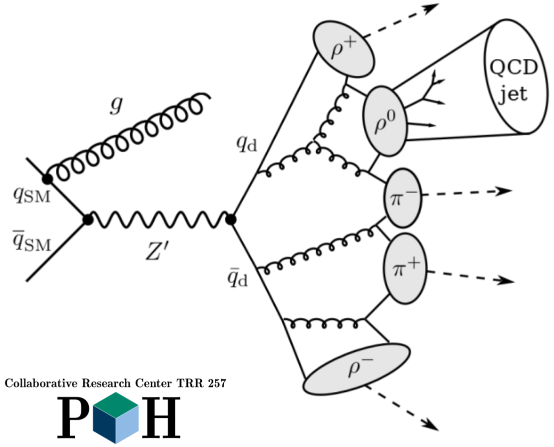


Figure: E. Bernreuther, NH, F. Kahlhoefer, S. Kulkarni [2311.17157]

Some very interesting questions left for future work (hopefully):

- What are the sensitivities of existing and upcoming collider experiments to the ρ_D decay?
- Can we detect and/or distinguish such a dark sector in other ways?
  (Like in indirect detection experiments or effects on astrophysical objects such as dark matter haloes?)



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Backup slide

Displaced vertices

Signature will highly depend on multiplicity of ρ_D

Significantly affected by:

- m_{ρ_D} $(m_{Z'}, \tau_{\rho_D})$
- Probability to create ρ_D over π_D in the shower

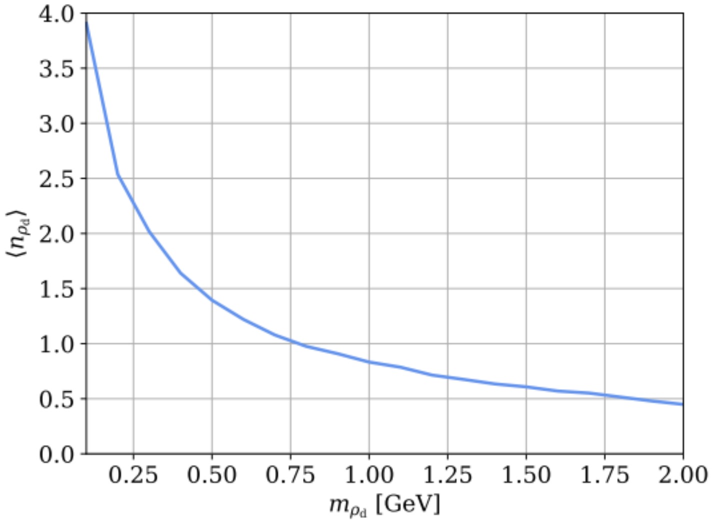

Figure: E. Bernreuther, T. Ferber, F. Kahlhoefer, A. Morandini et al. (2022)

Projected sensitives at Belle II

Projected sensitives explored in E. Bernreuther, T. Ferber, F. Kahlhoefer, A. Morandini et al. (2022)

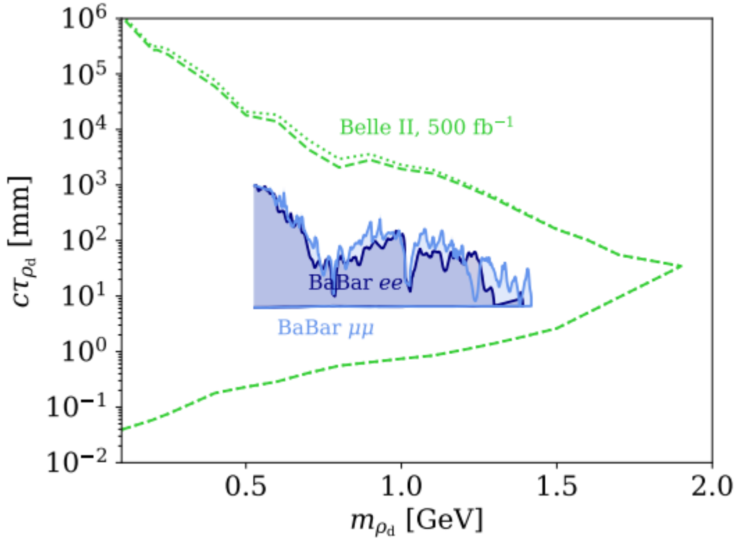

Figure: E. Bernreuther, T. Ferber, F. Kahlhoefer, A. Morandini et al. (2022)

Backup slide

Thermal width

$$\Gamma_{\rm th} = \frac{8\pi(N_{f_D}^2 - 1)}{x^2} e^{-x} m_{\pi_D}^3 \sigma_c$$

With the 2-pion scattering cross section

$$\sigma_c \approx \frac{1}{64\pi} \frac{3N_{f_D}^4 - 2N_{f_D}^2 + 6}{N_{f_D}^2 (N_{f_D}^2 - 1)} \frac{m_\pi^2}{f_\pi^4}$$
$$= \frac{3}{64\pi} \frac{m_\pi^2}{f_\pi^4} (1 + \mathcal{O}(N_{f_D}^{-2}))$$

Thermal width is exponentially suppressed at low temperatures due to low number density of pions.

Thermal width contributes <1% in region of interest.

See details in **[2311.17157]**

Backup slide

Bullet Cluster constraints

THE MISMEASURE OF MERGERS: REVISED LIMITS ON SELF-INTERACTING DARK MATTER IN MERGING GALAXY CLUSTERS

David Wittman[1,2], Nathan Golovich[1], William A. Dawson[3]

Draft version December 13, 2018

ABSTRACT

In an influential recent paper, Harvey et al. (2015) derive an upper limit to the self-interaction cross section of dark matter ($\sigma_{\rm DM}/m < 0.47$ cm^2/g at 95% confidence) by averaging the dark matter-galaxy offsets in a sample of merging galaxy clusters. Using much more comprehensive data on the same clusters, we identify several substantial errors in their offset measurements. Correcting these errors relaxes the upper limit on $\sigma_{\rm DM}/m$ to $\lesssim 2$ cm^2/g, following the Harvey et al. (2015) prescription for relating offsets to cross sections in a simple solid body scattering model. Furthermore, many clusters in the sample violate the assumptions behind this prescription, so even this revised upper limit should be used with caution. Although this particular sample does not tightly constrain self-interacting dark matter models when analyzed this way, we discuss how merger ensembles may be used more effectively in the future. We conclude that errors inherent in using single-band imaging to identify mass and light peaks do not necessarily average out in a sample of this size, particularly when a handful of substructures constitute a majority of the weight in the ensemble.

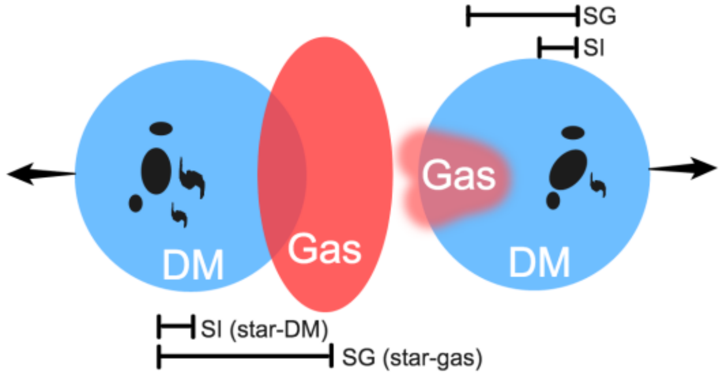

Fig. 1.— Schematic merger scenario: two subclusters have passed through each other, and the gas associated with each has slowed due to momentum exchange. This is observable as an offset between the star (i.e., galaxy) and gas positions, δ_{SG}. In analogy, any star-DM offset δ_{SI} may be attributed to momentum exchange between the DM halos and thus related to a cross section $\sigma_{\rm DM}/m$. Subcluster masses and gas densities may vary considerably.

See also: A. Robertson, R. Massey and V. Eke (2016) for similar discussions

Figure and description from D. Wittman, N. Golovich and W. A. Dawson (2017)

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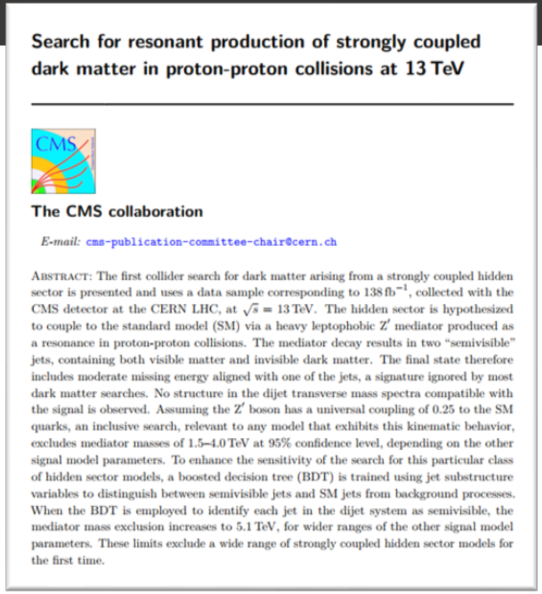
Search for resonant production of strongly coupled dark matter in proton-proton collisions at 13 TeV

The CMS collaboration

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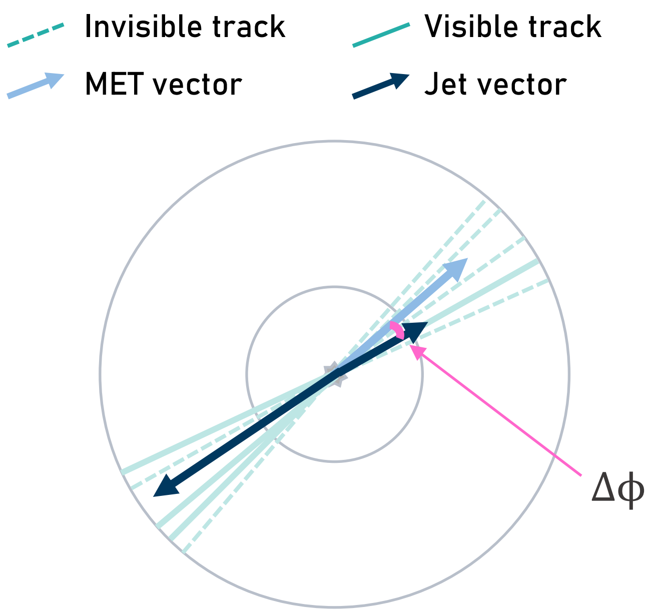
ABSTRACT: The first collider search for dark matter arising from a strongly coupled hidden sector is presented and uses a data sample corresponding to 138 fb^{-1}, collected with the CMS detector at the CERN LHC, at $\sqrt{s} = 13$ TeV. The hidden sector is hypothesized to couple to the standard model (SM) via a heavy leptophobic Z' mediator produced as a resonance in proton-proton collisions. The mediator decay results in two "semivisible" jets, containing both visible matter and invisible dark matter. The final state therefore includes moderate missing energy aligned with one of the jets, a signature ignored by most dark matter searches. No structure in the dijet transverse mass spectra compatible with the signal is observed. Assuming the Z' boson has a universal coupling of 0.25 to the SM quarks, an inclusive search, relevant to any model that exhibits this kinematic behavior, excludes mediator masses of 1.5–4.0 TeV at 95% confidence level, depending on the other signal model parameters. To enhance the sensitivity of the search for this particular class of hidden sector models, a boosted decision tree (BDT) is trained using jet substructure variables to distinguish between semivisible jets and SM jets from background processes. When the BDT is employed to identify each jet in the dijet system as semivisible, the mediator mass exclusion increases to 5.1 TeV, for wider ranges of the other signal model parameters. These limits exclude a wide range of strongly coupled hidden sector models for the first time.

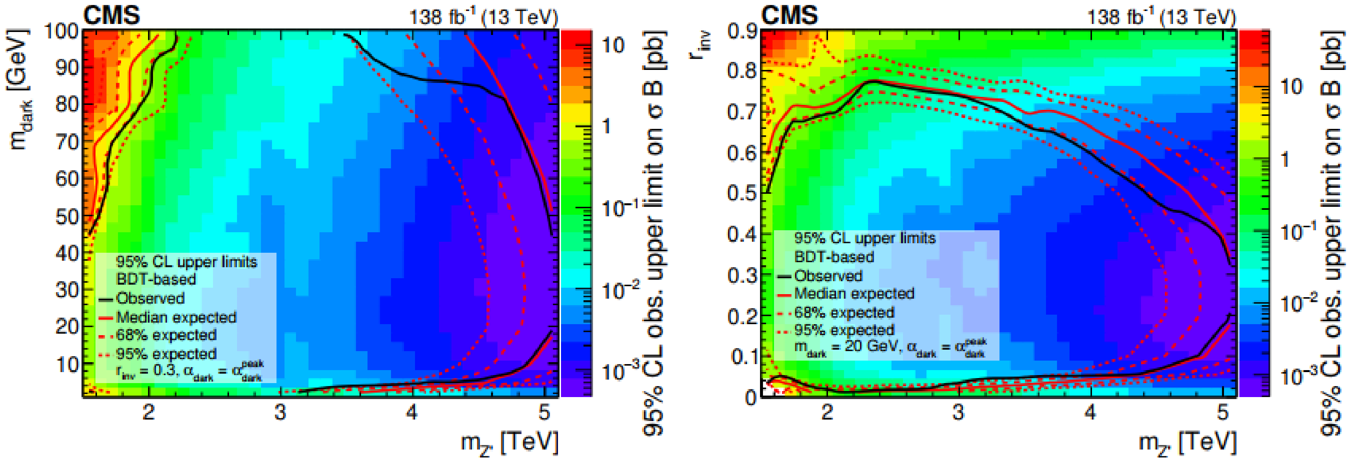
Dark shower signatures: Semi-visible jets



Events with small Δϕ look like QCD background. Such events are discarded to eliminate QCD background

⇨ Unexplored signature!

CMS published the first collider search for semi-visible jets in 2021 [2112.11125] (sensitive only to GeV-scale DM)



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Chiral Lagrangian

$$\mathcal{L}_{Ch} \supset \frac{f_{\pi_D}^2}{4}\mathrm{Tr}\left(D_\mu U D^\mu U\right) + \left[\frac{\mu_D^3}{2}\mathrm{Tr}\left(\mathrm{M}_q U^\dagger\right) + \mathrm{h.c.}\right]$$

With $U \equiv e^{2i\boldsymbol{\pi}_D/f_{\pi_D}}$, $D_\mu = \partial_\mu U + i g_{\pi_D\pi_D\rho_D}\left[U, \rho_{D_\mu}\right]$, and $g_{\pi_D\pi_D\rho_D} \approx \frac{m_{\rho_D}}{\sqrt{2} f_{\pi_D}}$

↓

$$\mathcal{L}_{Ch} \supset \frac{f_\pi^2}{4}\mathrm{Tr}\left(D_\mu \pi_D D^\mu \pi_D\right) + m_{\pi_D}^2 \mathrm{Tr}(\pi_D^2) + \frac{m_{\pi_D}^2}{3 f_\pi^2}\mathrm{Tr}(\pi_D^4) - \frac{2}{3 f_\pi^2}\mathrm{Tr}(\pi_D^2 D_\mu \pi_D D^\mu \pi_D - \pi_D D_\mu \pi_D \pi_D D^\mu \pi_D)$$

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Dark shower signatures

- Visible prompt

All DS particles decayed to the SM promptly

SM jet originating from the DS
SM-like

- Visible displaced

All DS particles decayed to the

Displaced vertex and emerging jets
Distinct from SM

- Invisible

All DS particles were s

MET – requires ISR to detect
WIMP-like

- Semi-visible

Some DS particles were sta
and some DS particles deca

MET aligned with jets
Distinct from SM

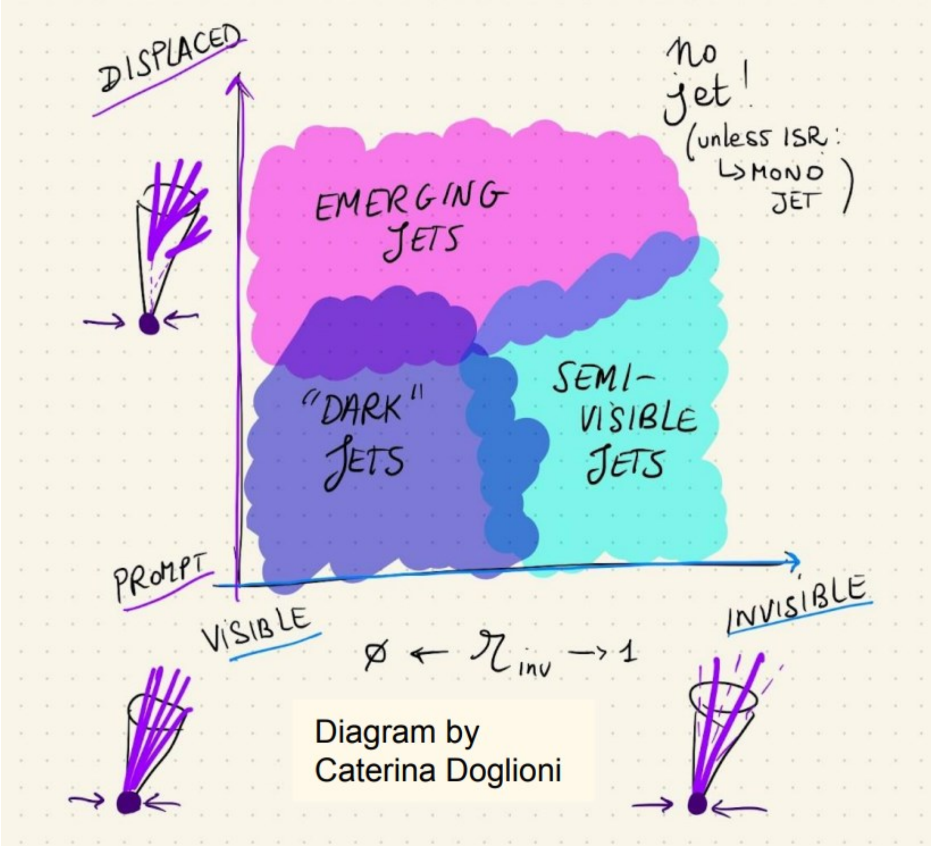

Diagram by
Caterina Doglioni

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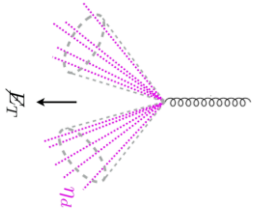
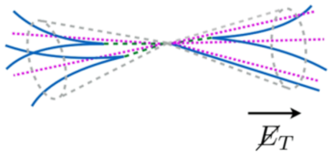
Dark showers can come in (roughly) 3 different forms:

Invisible



All DS particles were stable → MET opposite some ISR jet → **WIMP-like**

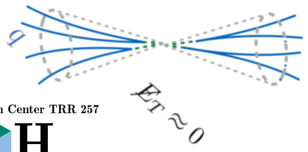
Semi-visible



Mix of stable DS particles and unstable DS that decayed to SM → MET aligned with jets → **distinct from SM**

→ Unstable DS particles (ρ_D) can give displaced vertices if long-lived → **distinct from SM**

Visible



All DS particles decayed to SM → SM jet if decays are prompt → **SM-like**

→ Unstable DS particles (ρ_D) can give displaced vertices if long-lived → **distinct from SM**

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