Karlsruher Institut für Technologie

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Strongly interacting dark sectors and dark showers

Nicoline Hemme

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Annual Meeting 2024 of the CRC TRR 257

Outline

Introduction to strongly interacting dark sectors

Dark showers and signatures

Strongly interacting dark sectors at colliders

Strongly interacting dark sectors as dark matter

Summary + Q&A

Introduction to strongly interacting dark sectors

High Energy Theory

SU(N_{c_D}) gauge group with N_{f_D} quark-like dark particles and gluon-like mediators described by the Lagrangian

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

Note: Quarks often assumed to be mass-degenerate for simplicity

Introduction to strongly interacting dark sectors

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Add a portal to the SM – many ways to do this
Example that will be useful in this talk:

New U(1)’ symmetry under which both
SM quarks and DS quarks
are charged and gives rise to massive mediator Z’

Introduction to strongly interacting dark sectors

At low energies, defined as $E \lesssim \Lambda_D$, chiral symmetry breaks and we need a new description; chiral effective field theory

Introduction to strongly interacting dark sectors

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Low Energy Theory

The chiral Lagrangian is

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

with SU(N) matrix $\mathrm{U} \equiv \exp(2\pi i / f_\pi)$

Introduction to strongly interacting dark sectors

High Energy Theory

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with SU(N) matrix $\mathrm{U} \equiv \exp(2\pi i / f_\pi)$

Quarks confine → bound states form
→ we get dark mesons such as

- dark pions π_D (pseudo-scalar)
- dark rho mesons ρ_D (vector)

They can carry the dark charge from U(1)'

Introduction to strongly interacting dark sectors

Disclaimer: This is not an exhaustive talk of strongly interacting dark sectors
This talk focuses on QCD-like SU(N) dark sectors but you can have:

Stable bound states from Sp(4) gauge theory

F. Zierler, S. Kulkarni, A. Maas, S. Mee, M. Nikolic, and J. and Pradler [2211.11272]

Dark sector glueballs

See e.g. K.K. Boddy, J.L. Feng, M. Kaplinghat, and T.M.P. Tait [1402.3629],
N. Yamanakaa, H. Iida, A. Nakamurad, and M. Wakayama [1910.01440],
A. Batz, T. Cohen, D. Curtin, C. Gemmell, and G. D. Kribs [2310.13731]

Dark showers and signatures

SM particles collide at high energies and have a chance of producing the portal mediator

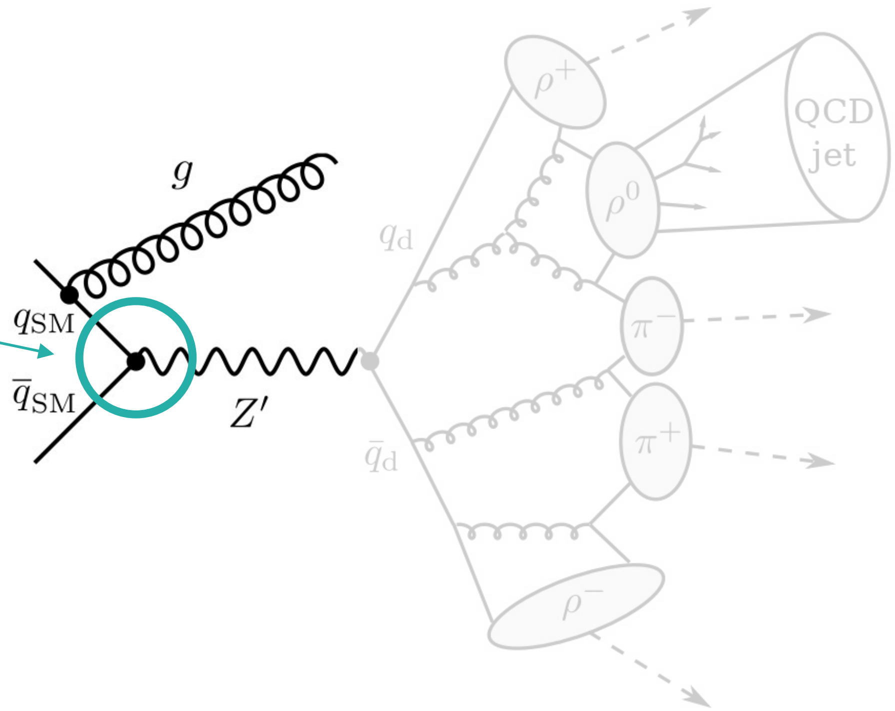


Figure: E. Bernreuther, F. Kahlhoefer, M. Krämer, P. Tunney [1907.04345]

Dark showers and signatures

Portal mediator may decay to DS pair of quark$_D$ and anti-quark$_D$

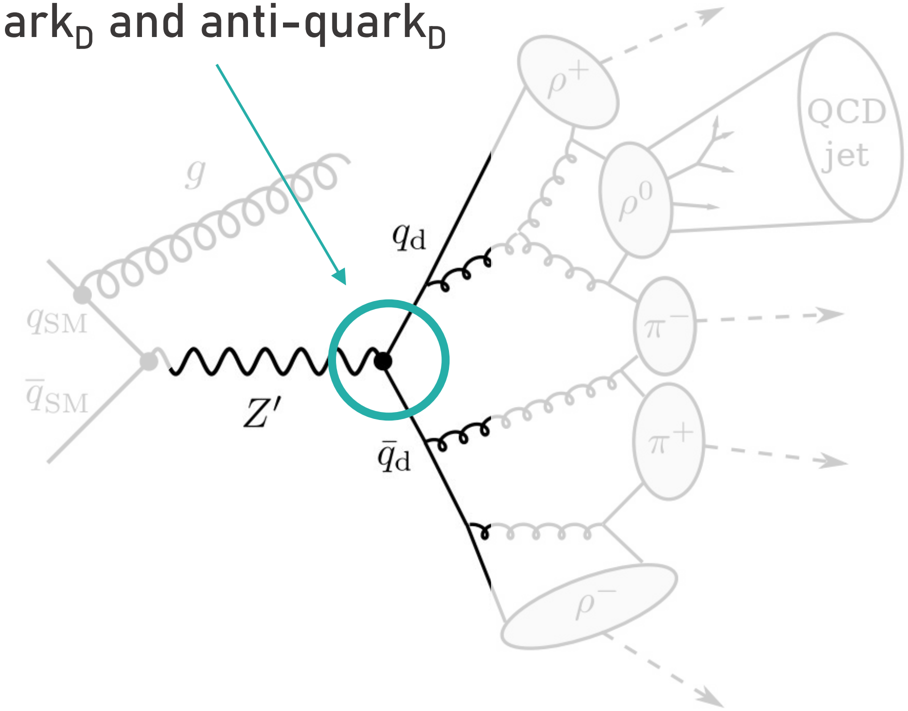
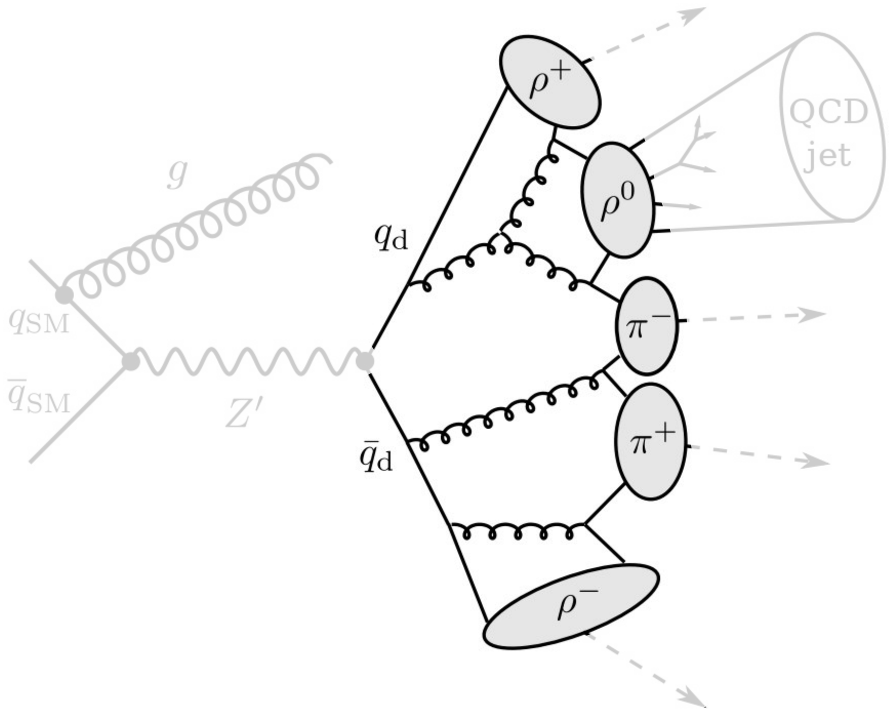


Figure: E. Bernreuther, F. Kahlhoefer, M. Krämer, P. Tunney [1907.04345]

Dark showers and signatures

Dark parton shower occurs in the dark sector – possibly resulting in many new dark bound states



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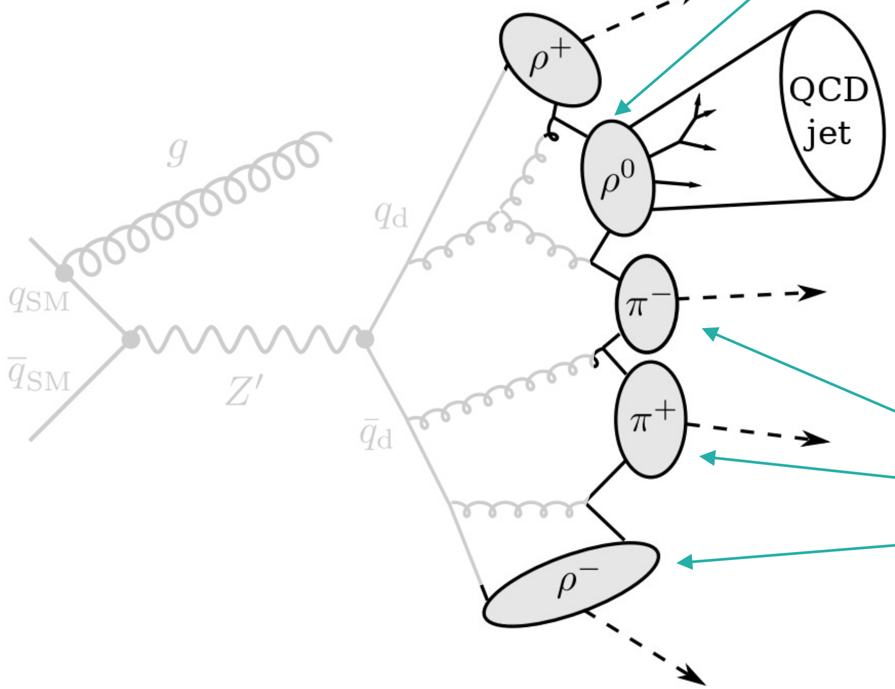

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Dark showers and signatures

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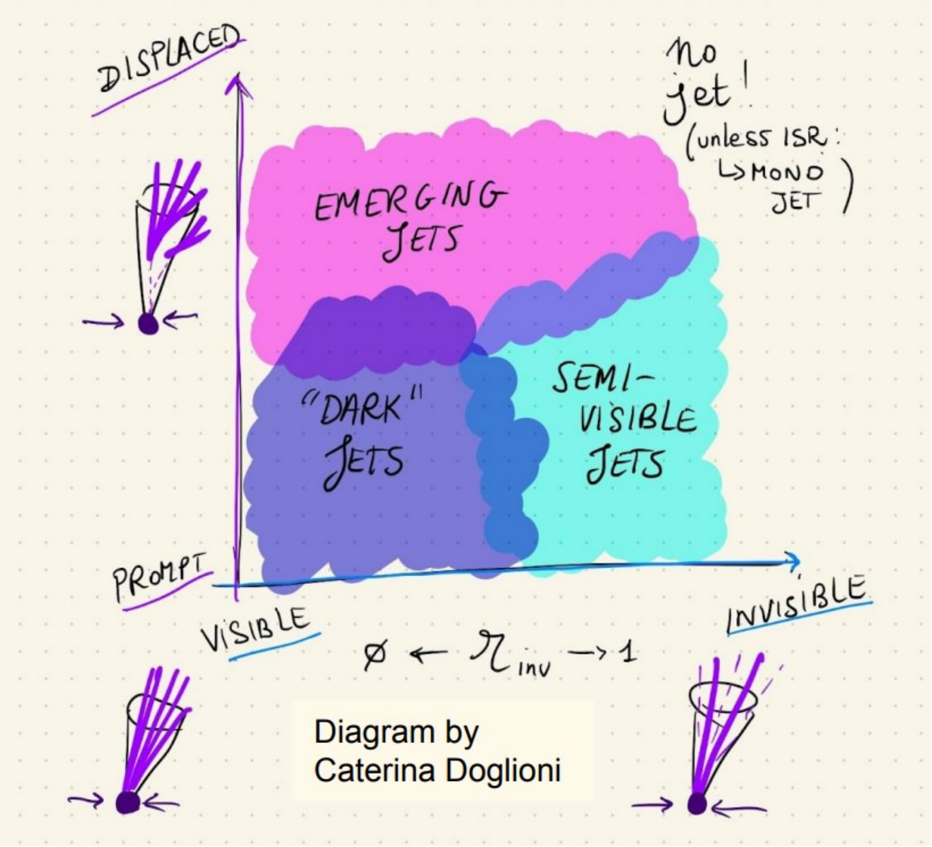


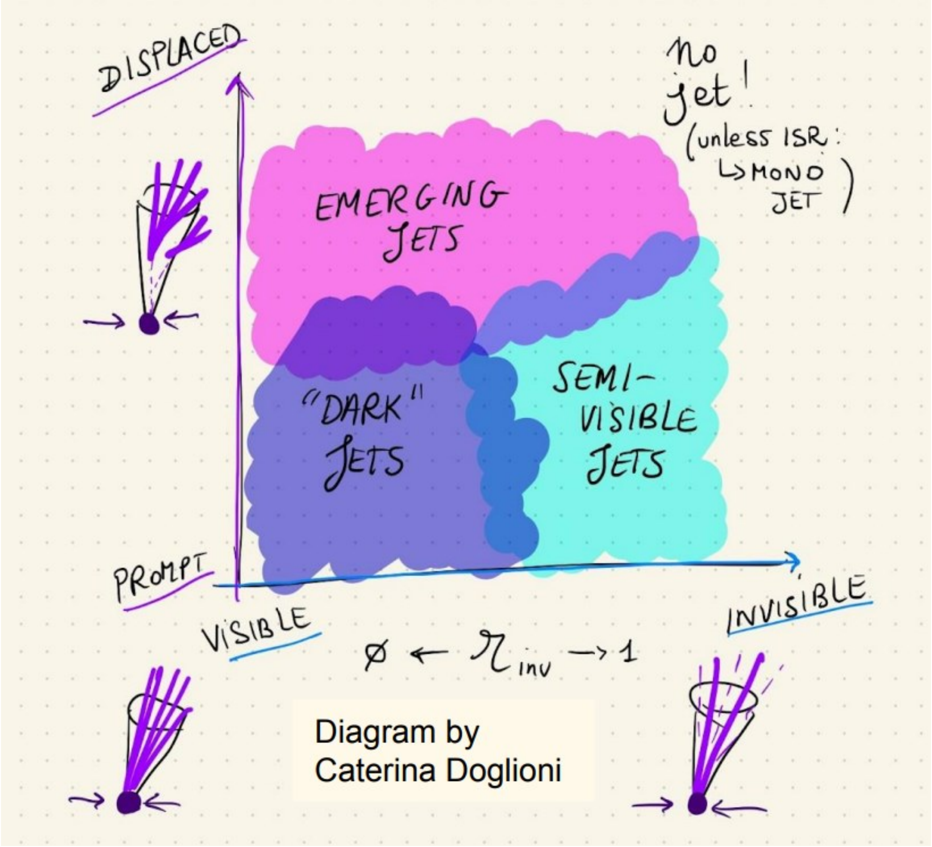
Dark showers and signatures

Dark shower signatures

SM-like

- Visible prompt – SM jet originating from the DS

All DS particles decayed to the SM promptly



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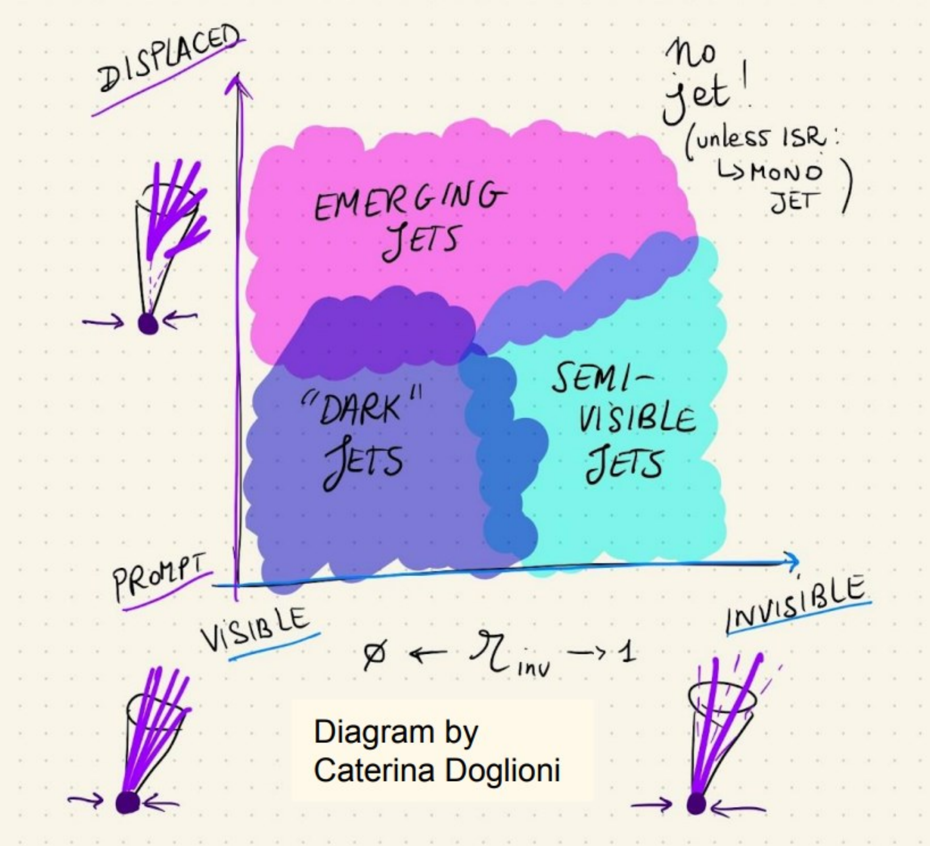
Distinct

- Visible displaced – Displaced vertices and emerging jets

All DS particles decayed to the SM but with a significant lifetime



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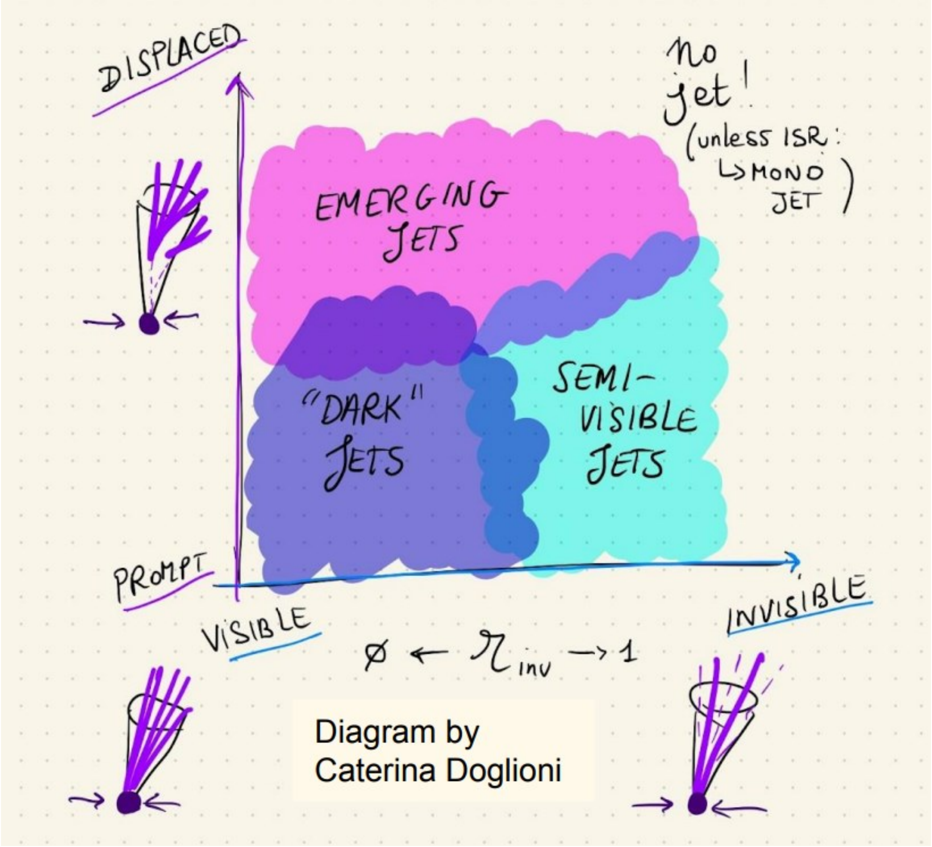
- Invisible – MET, requires ISR to detect

All DS particles were stable or very long lived

WIMP-like



Dark showers and signatures

Dark shower signatures

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- Invisible – MET, requires ISR to detect
All DS particles were stable or very long lived

WIMP-like

- Semi-visible – MET aligned with jet
Some DS particles were stable or very long lived
and some DS particles decayed to the SM

Distinct

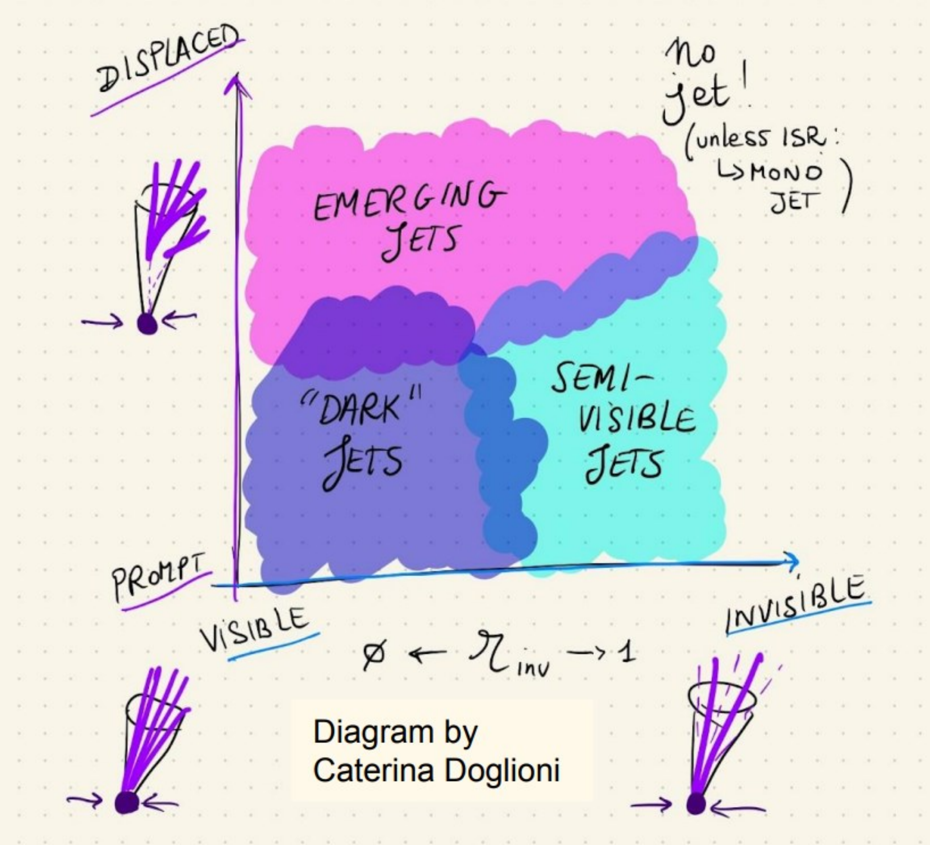
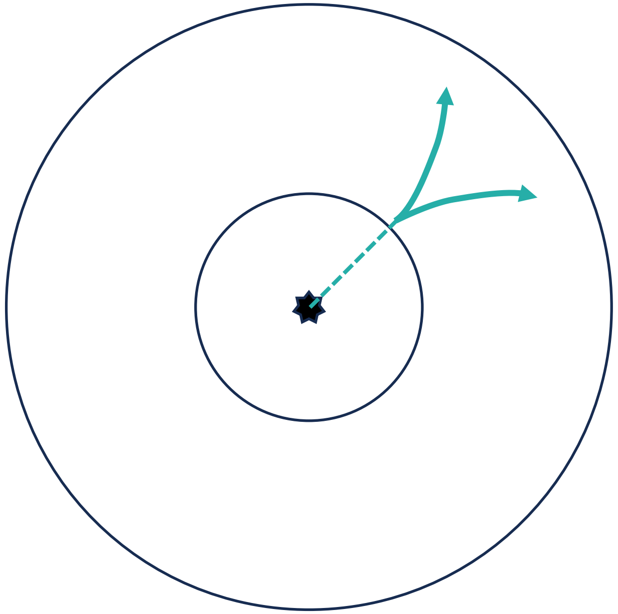


Diagram by
Caterina Doglioni

Strongly interacting dark sectors at colliders

Dark shower signatures: Displaced vertex

Invisible track
Visible track



Strongly interacting dark sectors at colliders

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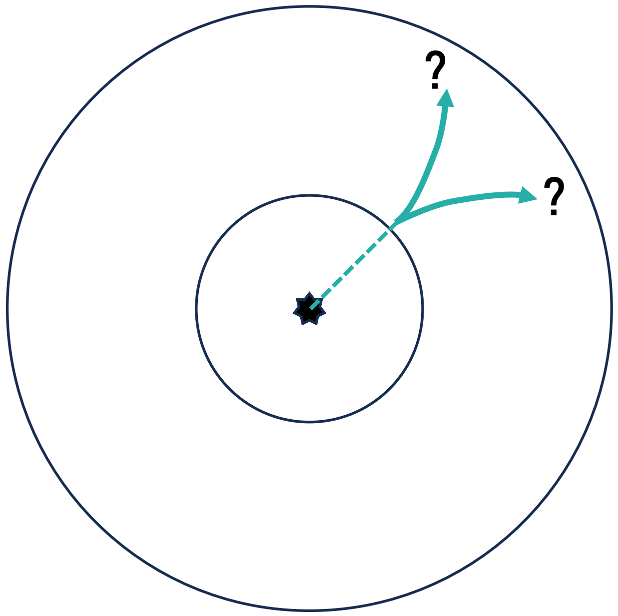

Final states depend on the portal of your choice

Or vice versa

Your experiment/search determines which portals you are sensitive to

Strongly interacting dark sectors at colliders

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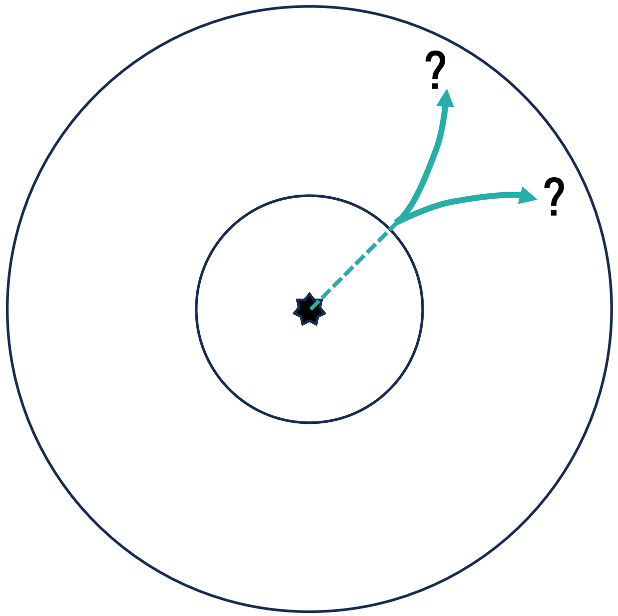

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Example: Displaced vertices at Belle II

$e^+e^- \to q_D\bar{q}_D$ can result in a dark shower with low multiplicity of dark particles, followed by $\rho_D \to l^+l^-$ or $\rho_D \to$ hadrons

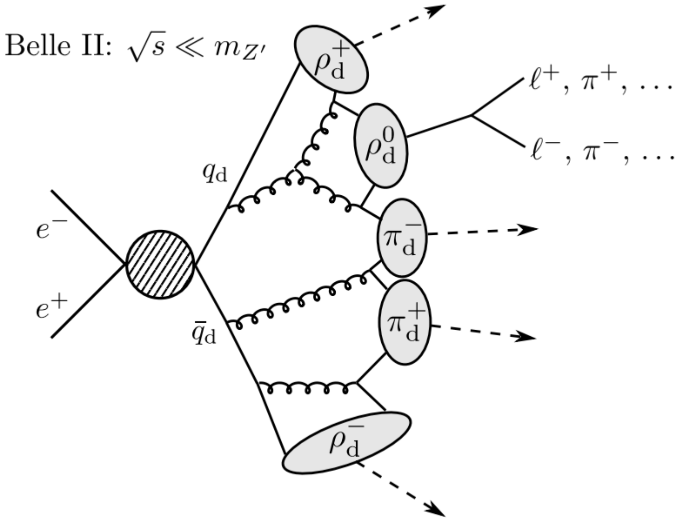

Figure: E. Bernreuther, T. Ferber, F. Kahlhoefer, A. Morandini et al. [2203.08824]

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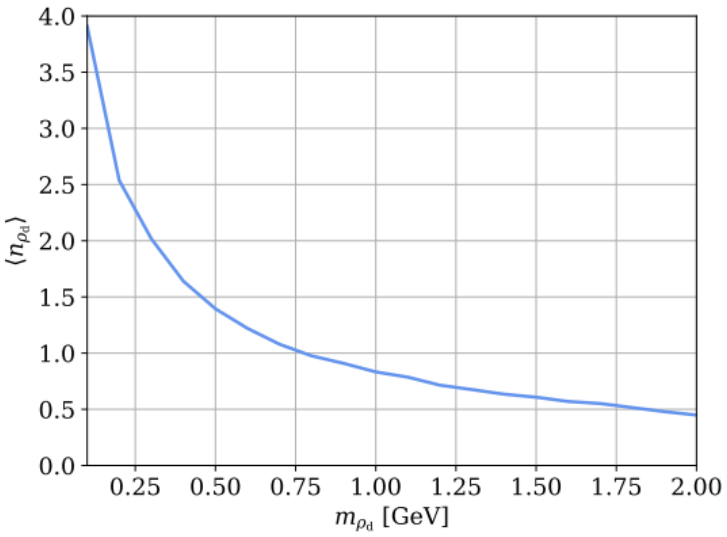
Strongly interacting dark sectors at colliders

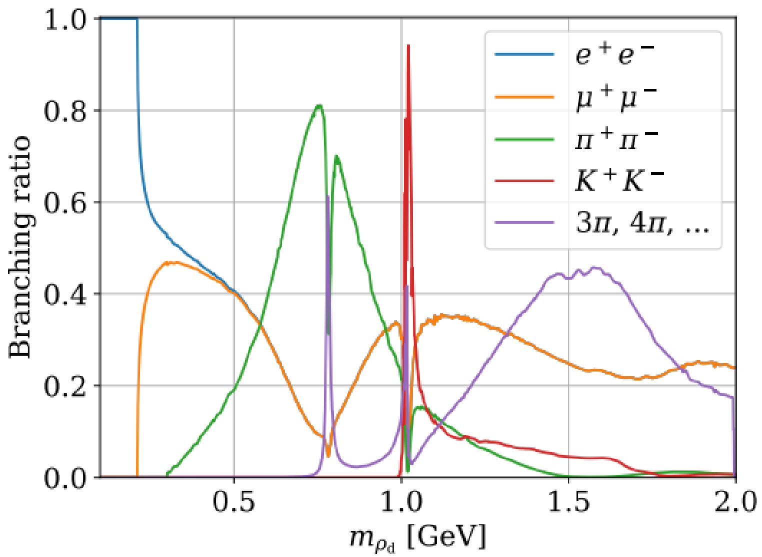
Forecasting dark showers at Belle II

E. Bernreuther, T. Ferber, F. Kahlhoefer, A. Morandini et al. [2203.08824]

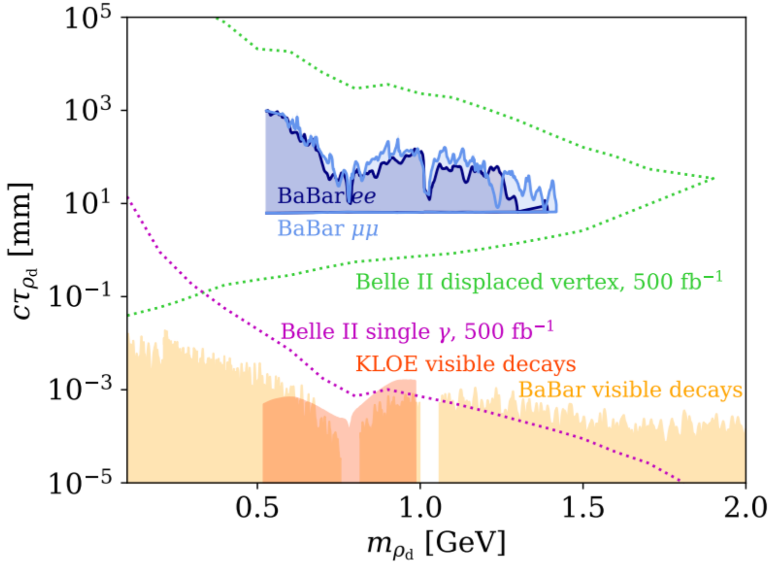
Single γ is $e^+e^- \to \gamma + \text{inv}$, i.e. it is assumed that the dark particles remain stable within the detector



Average multiplicity of ρ_D at Belle II ($\sqrt{s} = 10.58$ GeV)



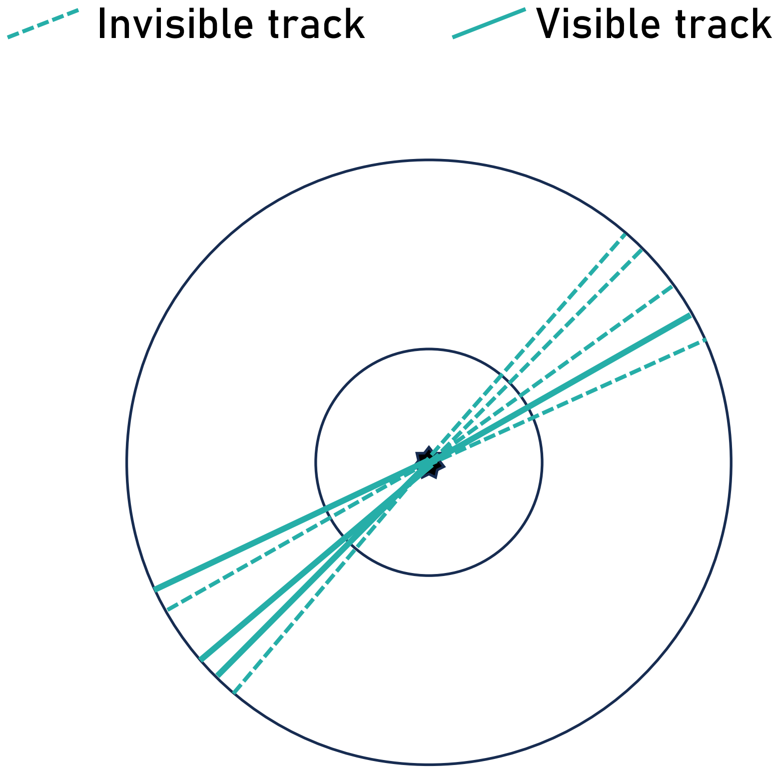
Branching ratios of the ρ_D as a function of its mass



Projected sensitivities at Belle II and existing bounds

Strongly interacting dark sectors at colliders

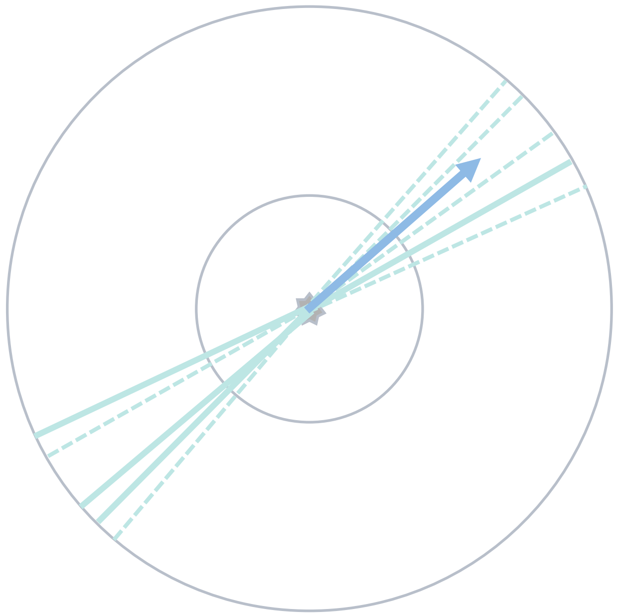
Dark shower signatures: Semi-visible jets



Strongly interacting dark sectors at colliders

Dark shower signatures: Semi-visible jets

Invisible track
Visible track
MET vector



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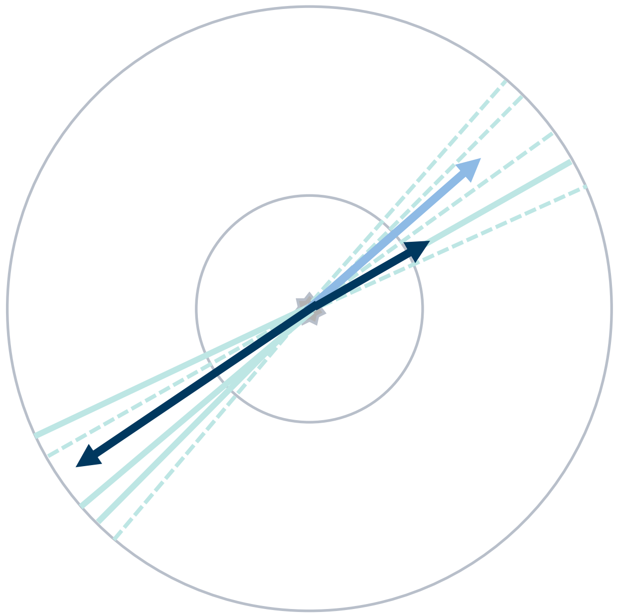

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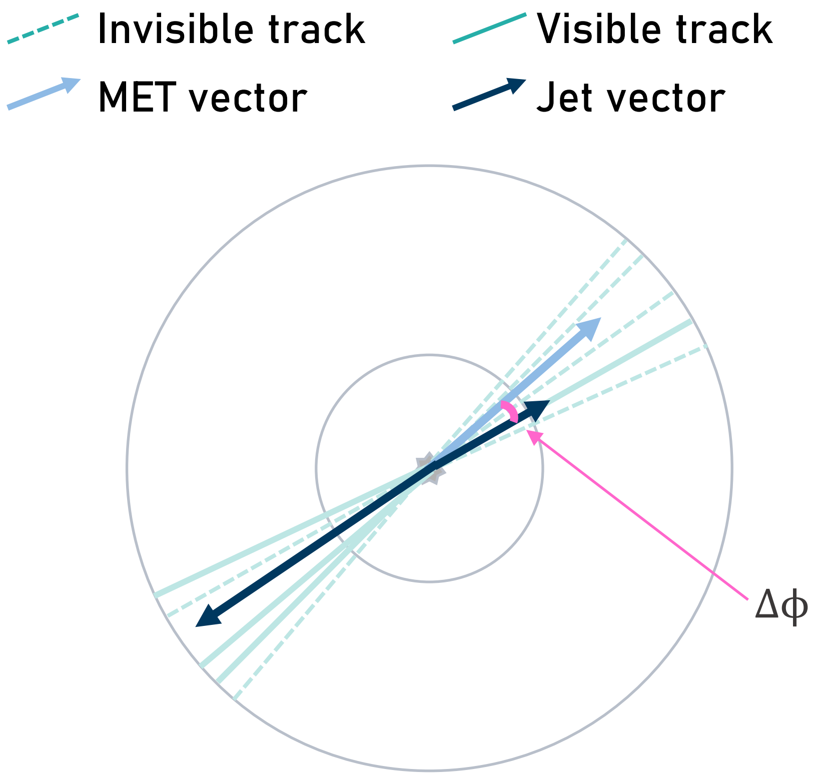

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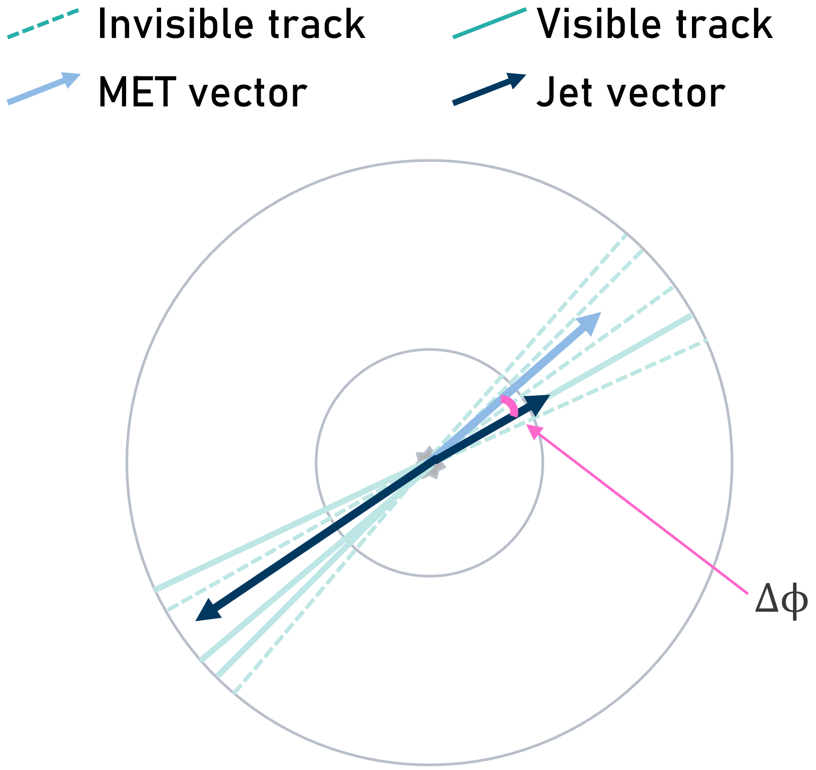
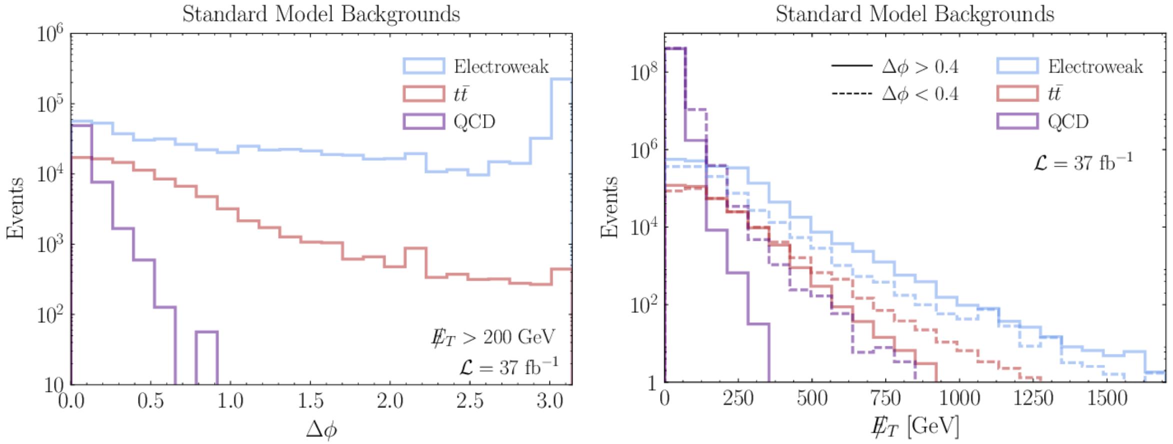


Events with small Δϕ look like QCD background



Ref: T. Cohen, M. Lisanti, H. K. Lou and S. Mishra-Sharma [1707.05326]

Such events are discarded to eliminate QCD background

⇨ Unexplored signature!

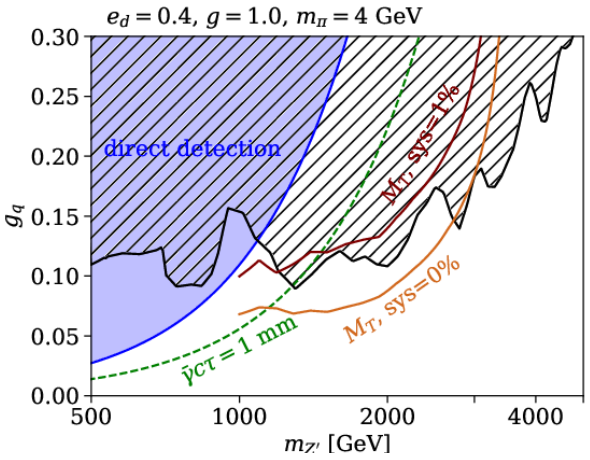
Strongly interacting dark sectors at colliders

Searches and existing constraints on semi-visible jets

Search variable: Transverse mass M_T turns out to be a good variable to search for new mediator Z' in semi-visible jet events

Proposed by T. Cohen, M. Lisanti, H.K. Lou [1503.00009]

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



Projected sensitivities and comparisons to existing constraints.

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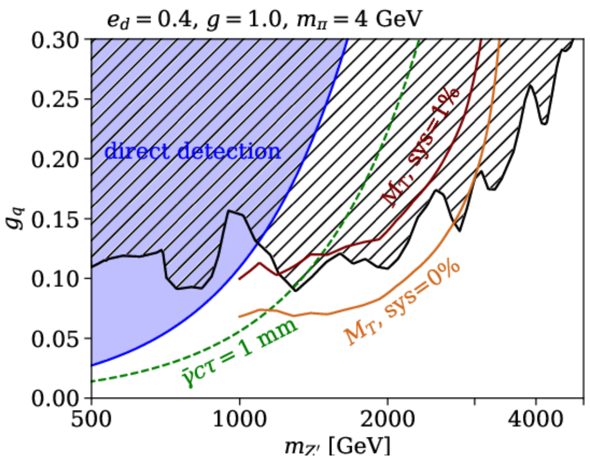

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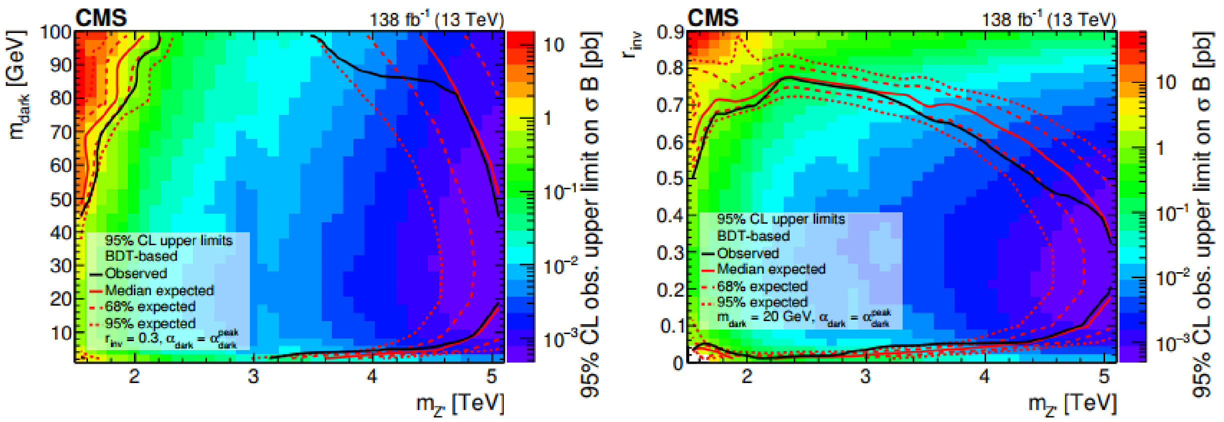
CMS published the first collider search for semi-visible jets in 2021 [2112.11125]

No discovery, but sensitive only to GeV-scale DM and implementation of model is inconsistent with theory
- does this change the phenomenology?



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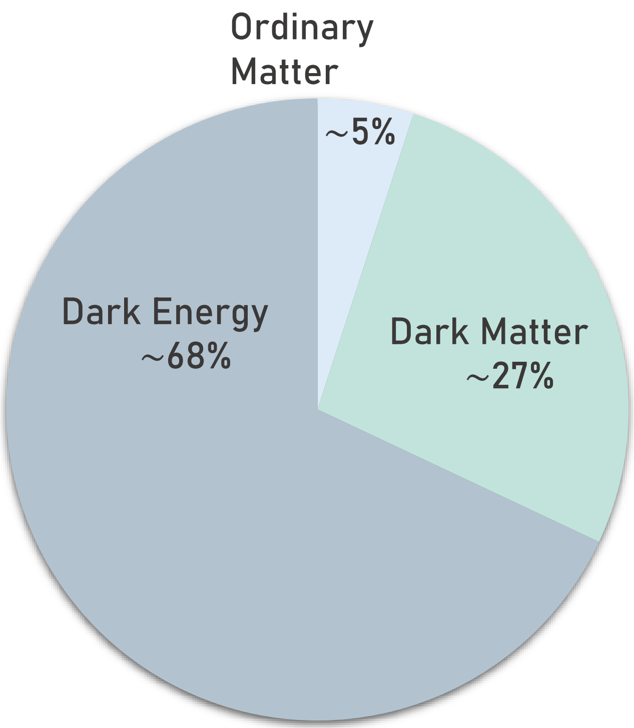
Strongly interacting dark sectors as dark matter

How can strongly interacting dark sectors give us a viable dark matter candidate?



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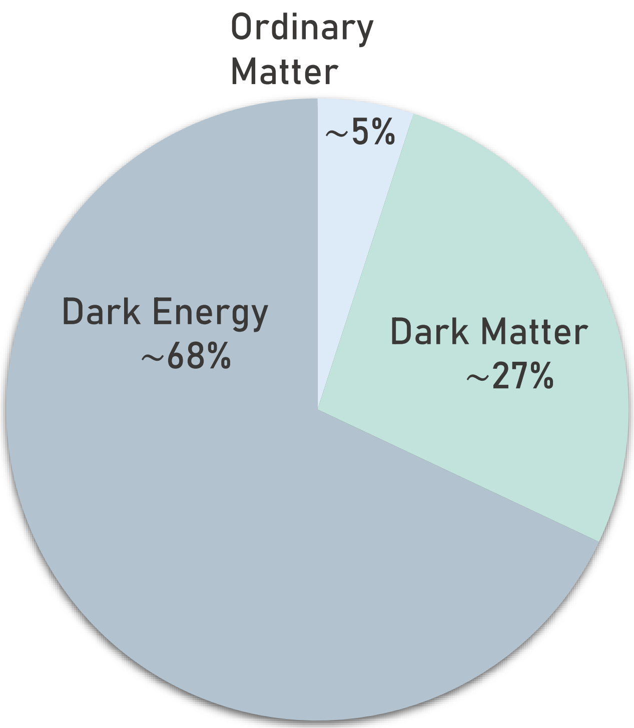

The dark sector can contain stable bound states

- Typical candidate is the pseudo-Goldstone boson, the dark pion π_D
- The dark pion stability can be ensured by
  - Parity symmetry
  - U(1)' symmetry (can also provide the portal)

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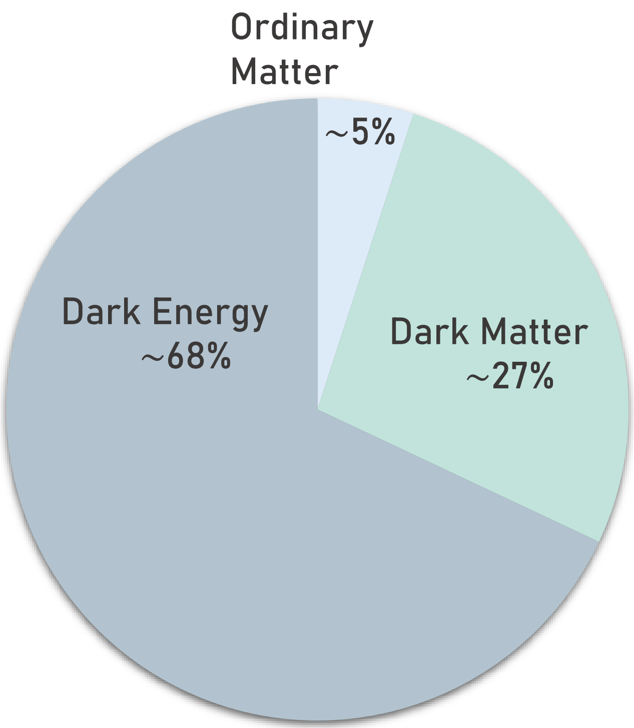

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Freeze-out of DM by number changing processes within the dark sector

- Original SIMP-miracle is $3\chi \rightarrow 2\chi$ (via WZW term), but this violates self-interaction bounds from the Bullet Cluster
- Many alternatives; Co-SIMP $2\chi+SM \rightarrow \chi+SM$, resonant enhancement or by light vector meson process $3\pi_D \rightarrow \pi_D \rho_D$

Strongly interacting dark sectors as dark matter

Dark matter relic density in strongly interacting dark sectors with light vector mesons

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

A QCD-like SU(N) theory will have vector mesons, ρ_D

If they are heavy, it is a fair assumption to neglect them (classical SIMP)

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! But this violates the Bullet Cluster constraints
(or overproduces dark matter)

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

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General SIMP cross section:

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

Lower mass → more efficient → lower relic abundance

Self-interaction cross section:

$$\frac{\sigma_{SI}}{m_\pi} \propto \frac{\xi}{m_\pi^3} \leq \text{BC constraint}$$

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What if they are light?
Specifically, $m_{\rho_D} < 2m_{\pi_D}$

This opens up the channel $3\pi_D \rightarrow \pi_D \rho_D$
and closes the $\rho_D \rightarrow \pi_D \pi_D$ decay channel

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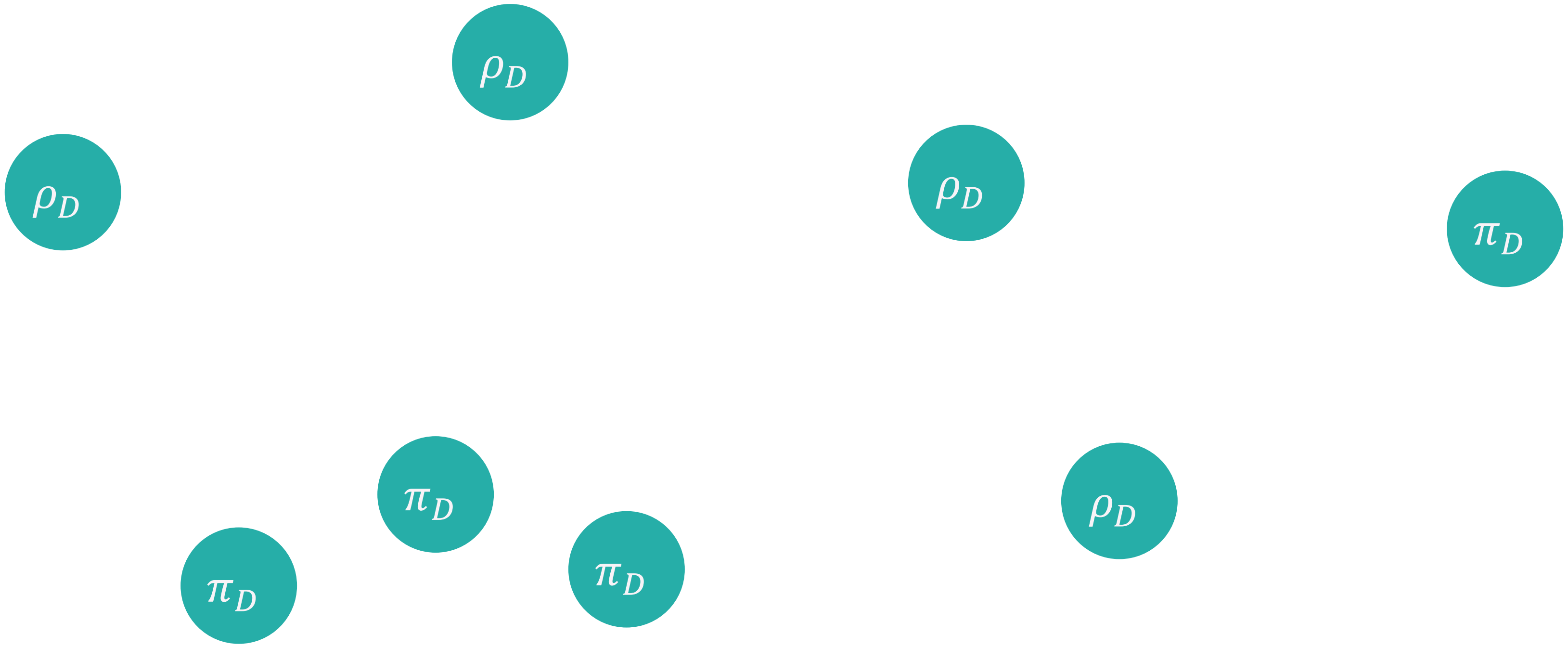
Strongly interacting dark sectors as dark matter

Early (hot) Universe

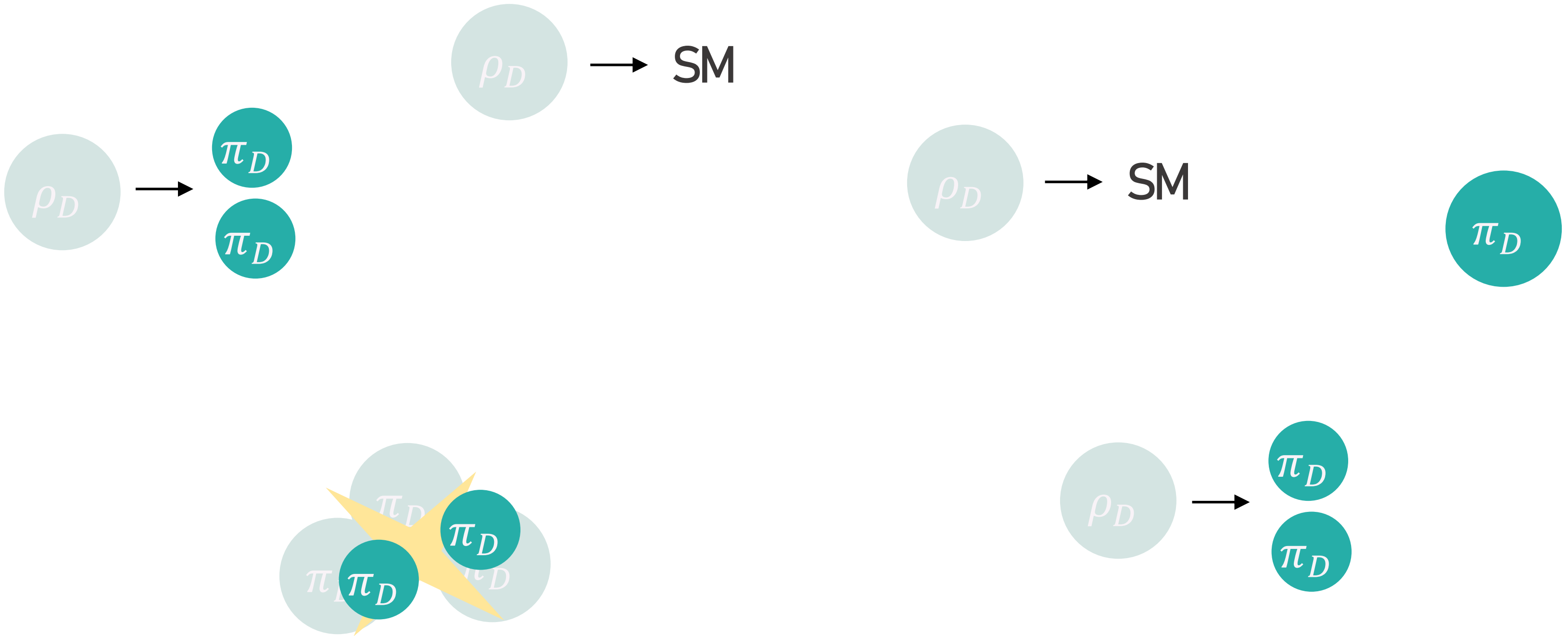
There is enough energy to produce many new particles



Strongly interacting dark sectors as dark matter

Freeze-out of dark matter with heavy ρ_D

Energy falls below threshold to produce more of these particles while some decay or annihilate



Strongly interacting dark sectors as dark matter

Relic abundance reached with heavy ρ_D

After freeze-out there are many stable dark pions remaining – it's hard to avoid overproducing DM

Strongly interacting dark sectors as dark matter

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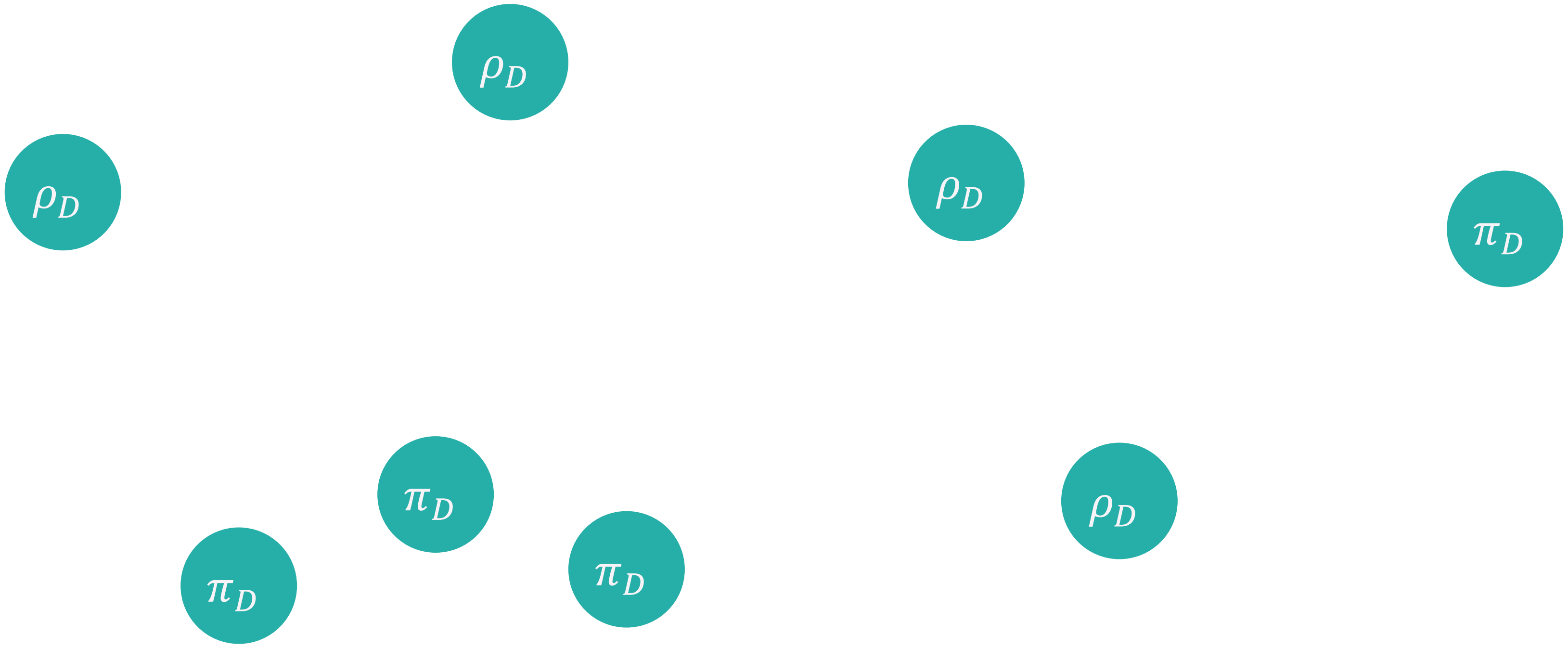

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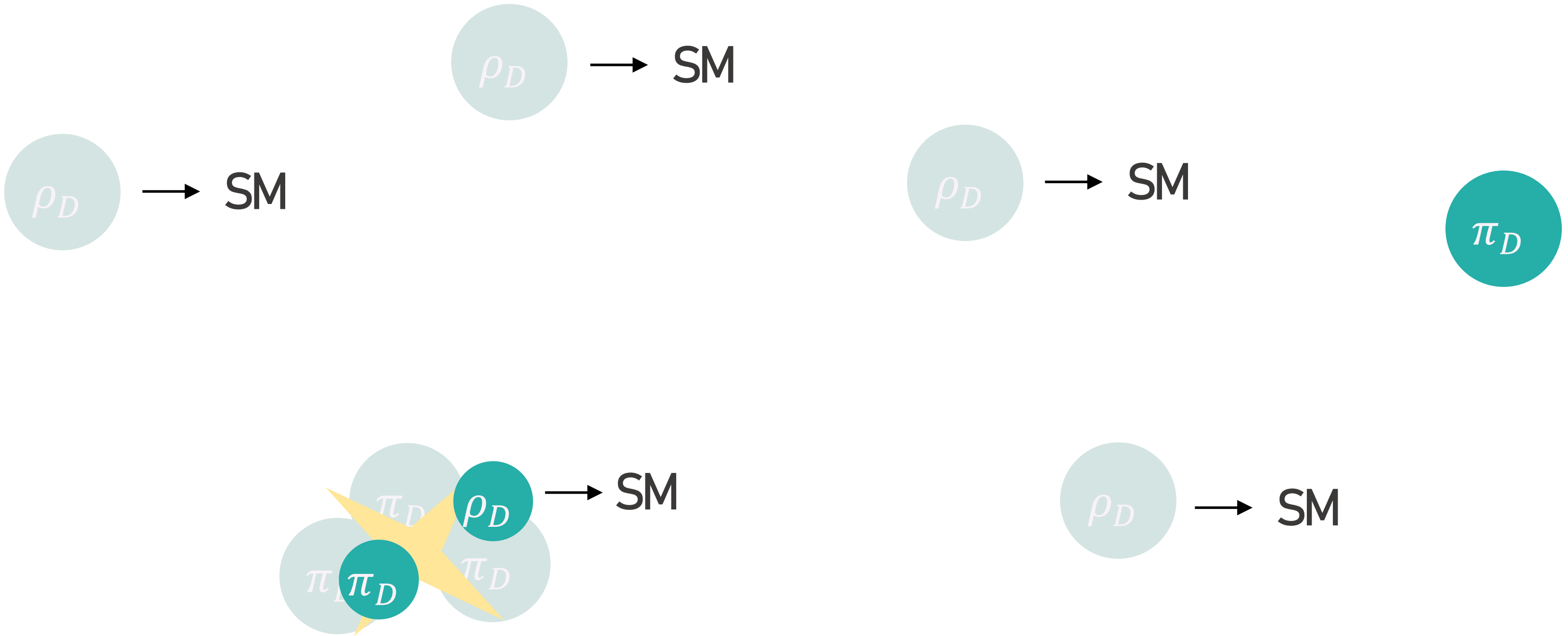

ρ_D are too light to decay to a pair of dark pions!

Strongly interacting dark sectors as dark matter

Relic abundance reached with light ρ_D

It is easier to avoid overproducing dark matter and reach the correct relic abundance

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Strongly interacting dark sectors as dark matter

Dark matter relic density in strongly interacting dark sectors with light vector mesons

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

If $m_{\rho_D} < 2m_{\pi_D}$, we must consider its interactions by promoting the derivative to the covariant derivative

$$D_\mu \pi_D = \partial_\mu \pi_D + \mathrm{i} g_{\pi_D \pi_D \rho_D} [\pi_D, \rho_{D\mu}]$$

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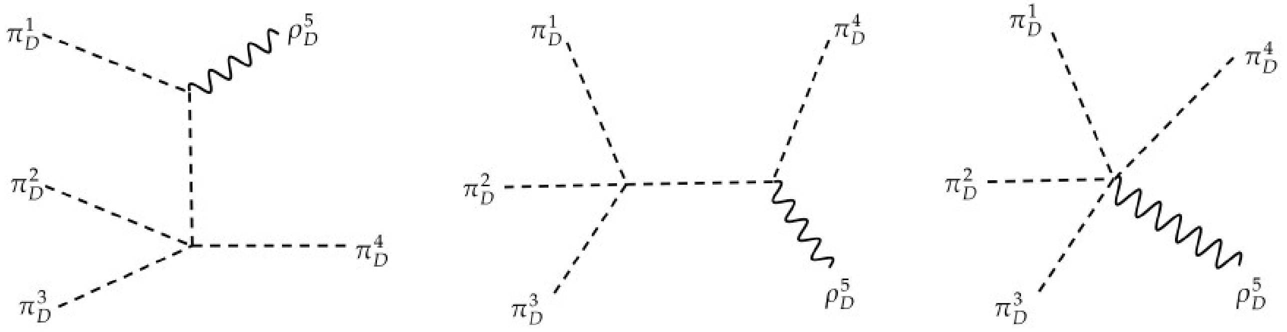
$$D_\mu \pi_D = \partial_\mu \pi_D + i g_{\pi_D \pi_D \rho_D} [\pi_D, \rho_{D\mu}]$$

Then, the chiral Lagrangian up to $\mathcal{O}(\pi^4)$ gives us the $3\pi_D \rightarrow \pi_D \rho_D$ interactions

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

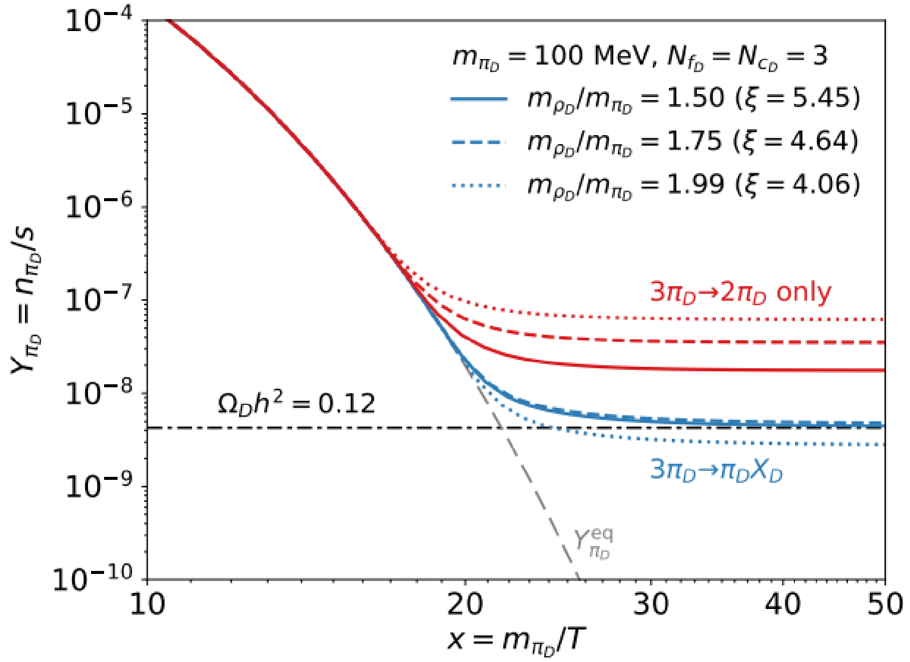
The model has 2 free parameters m_{π_D} and $\frac{m_{\rho_D}}{m_{\pi_D}}$ and we can relate to f_{π_D} via lattice calculations



Strongly interacting dark sectors as dark matter

Dark matter relic density in strongly interacting dark sectors with light vector mesons

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



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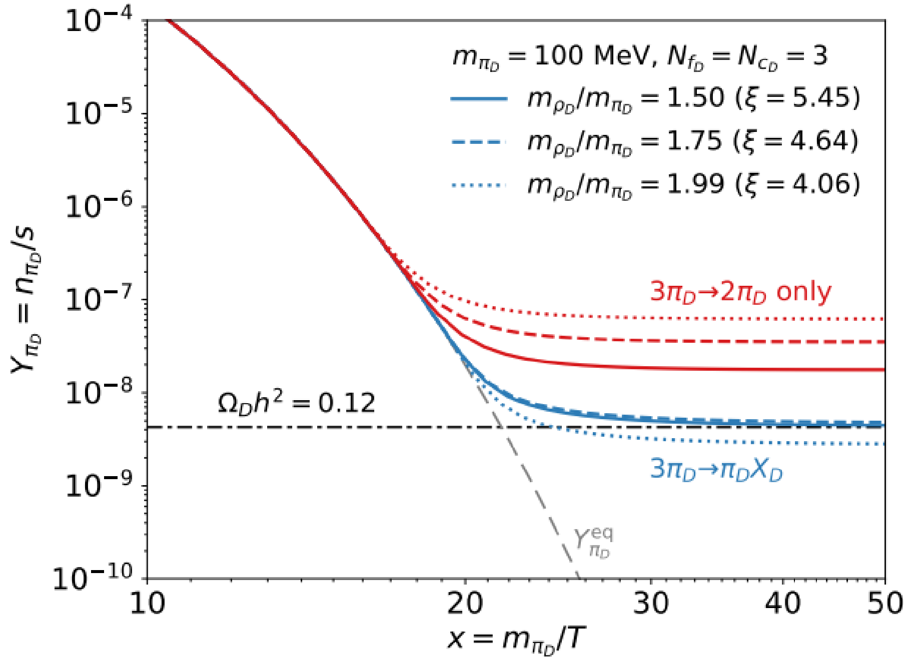

→ $3\pi_D \to \pi_D \rho_D$ dominates dark pion freeze-out

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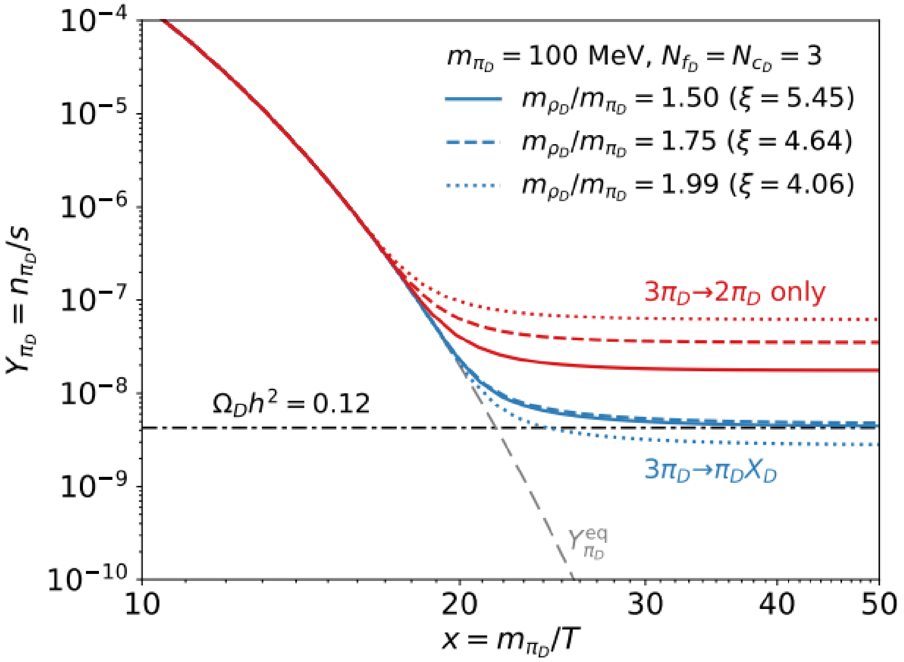

$3\pi_D \to \pi_D \rho_D$ **dominates dark pion freeze-out**

More efficient depletion of DM allows larger masses/smaller couplings

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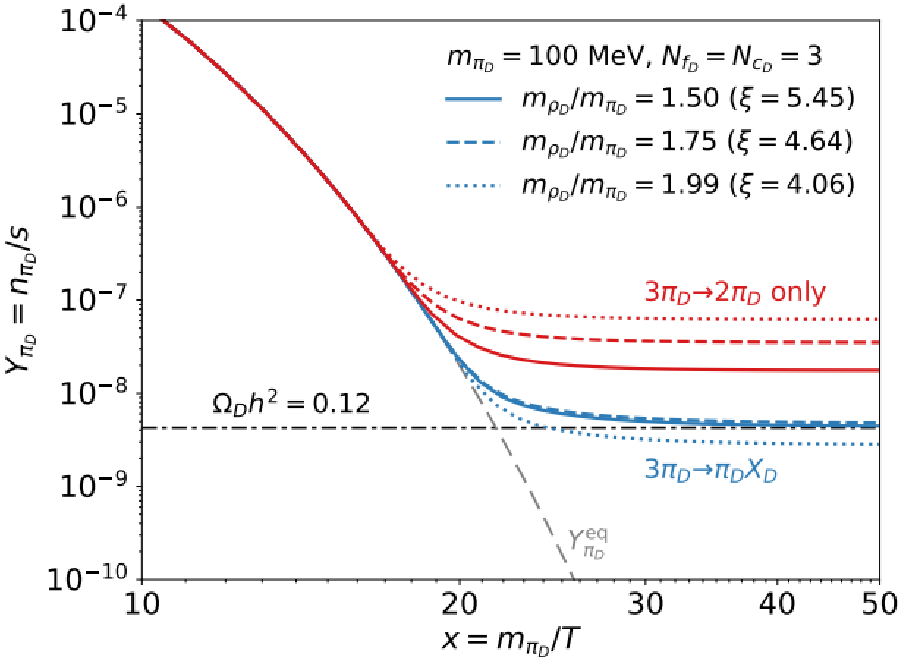

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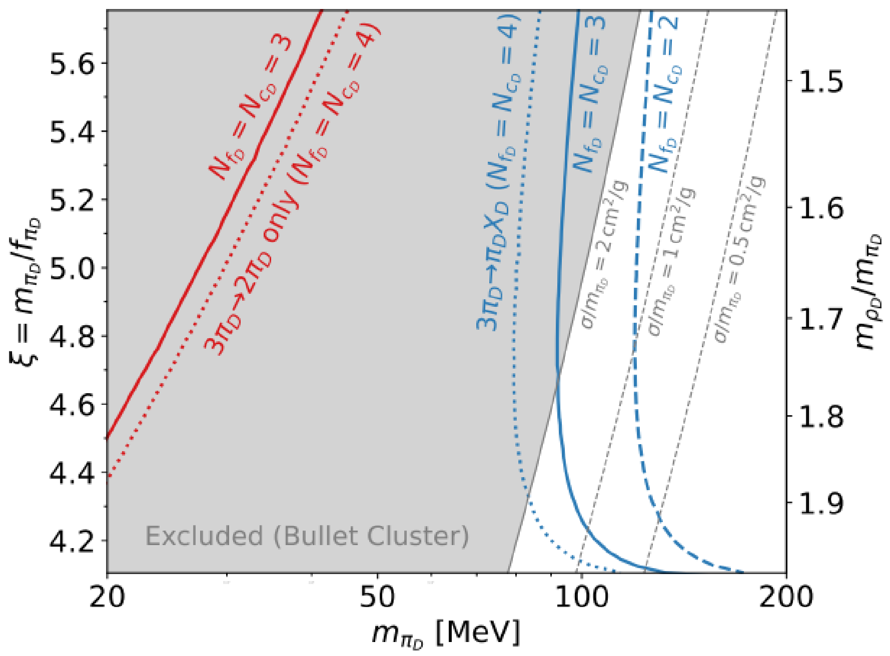


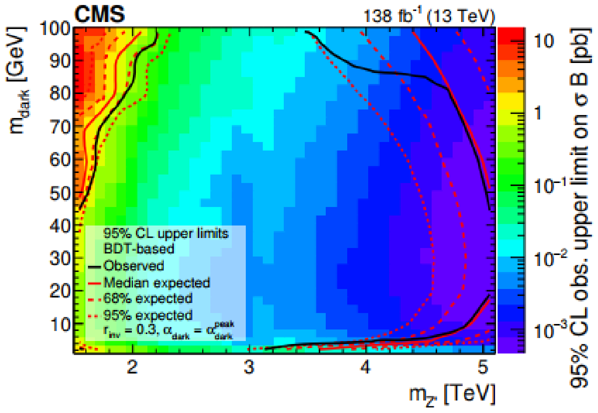
Strongly interacting dark sectors as dark matter

Strongly interacting dark sectors with light vector mesons

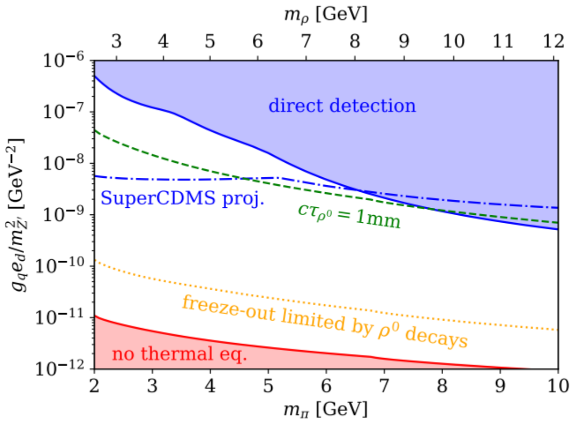
Cosmological arguments prefer **m_{DM} ~ 100–150 MeV**

Existing searches and constraints on similar models often consider a much higher mass range (except BC)

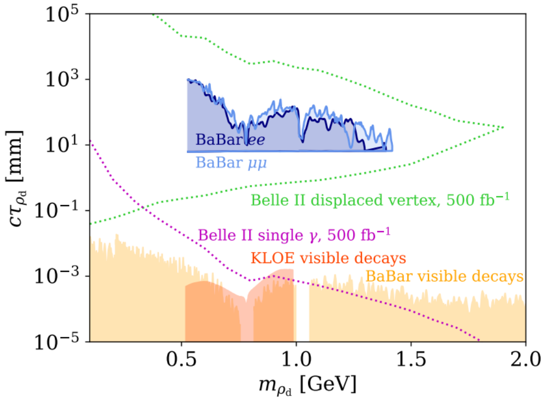
→ This is an unexplored model



Ref: The CMS collaboration [2112.11125]



Ref: E. Bernreuther, F. Kahlhoefer, M. Krämer, and P. Tunney [1907.04346]



Ref: E. Berneurther, T. Ferber, F. Kahlhoefer, A. Morandini et al. [2203.08824]

Strongly interacting dark sectors as dark matter

Strongly interacting dark sectors with light vector mesons

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→ **This is an unexplored model**

Open questions:

Strongly interacting dark sectors as dark matter

Strongly interacting dark sectors with light vector mesons

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Nicoline Hemme, nicoline.hemme@kit.edu - Institute for Theoretical Particle Physics, Karlsruhe Institute of Technology

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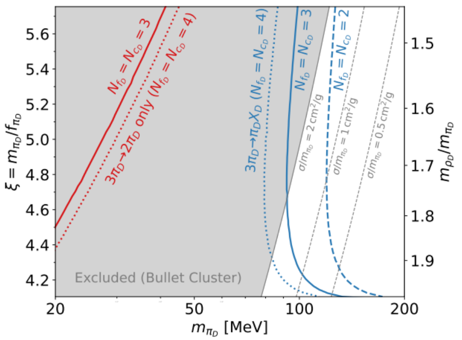
- PYTHIA 8.3 HV module is used to simulate dark showers – is it valid for sub-GeV dark pions?
- What could be the astrophysical signatures and/or bounds?

Summary + Q&A

A QCD-like strongly interacting dark sector can have dark mesons (like π_D and ρ_D)



π_D are often the DM candidates of these theories

- But they cannot be the only DS particles as they will violate the relic abundance or BC constraints

Recent work established that π_D freeze out dominantly via $3\pi_D \rightarrow \pi_D \rho_D$ if $m_{\rho_D} < 2m_{\pi_D}$

- The vector meson will always appear in a confining SU(N) theory – we just considered the case where it is light and there exists mixing with the SM (often assumed to ensure testable predictions)
- This enables the model to satisfy both the relic abundance and the BC constraints
- This ensures DS decays to SM which makes us optimistic for distinct signatures

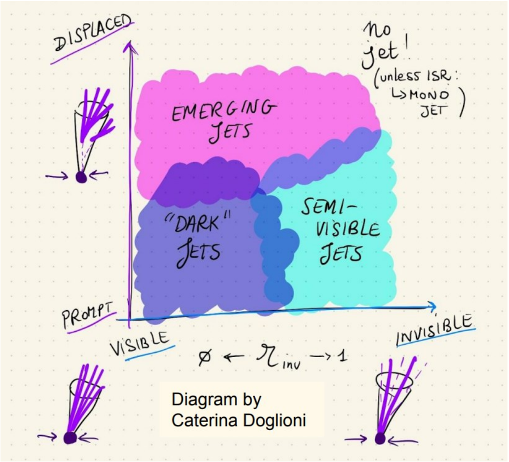


Diagram by Caterina Doglioni

ρ_D decays can give rise to displaced vertices and semi-visible jets

- These signatures are largely unexplored, especially at sub-GeV DM mass ranges

Nicoline Hemme, nicoline.hemme@kit.edu - Institute for Theoretical Particle Physics, Karlsruhe Institute of Technology

Lattice calculations

QCD modeling of hadron physics

P. Maris[a,b] and P.C. Tandy[b]

[a]Dept. of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260

[b]Center for Nuclear Research, Dept. of Physics, Kent State University, Kent OH 44242

We review recent developments in the understanding of meson properties as solutions of the Bethe–Salpeter equation in rainbow-ladder truncation. Included are recent results for the pseudoscalar and vector meson masses and leptonic decay constants, ranging from pions up to $c\bar{c}$ bound states; extrapolation to $b\bar{b}$ states is explored. We also present a new and improved calculation of $F_\pi(Q^2)$ and an analysis of the $\pi\gamma\gamma$ transition form factor for both $\pi(140)$ and $\pi(1330)$. Lattice-QCD results for propagators and the quark-gluon vertex are analyzed, and the effects of quark-gluon vertex dressing and the three-gluon coupling upon meson masses are considered.

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

P. Maris and P. C. Tandy, Nucl. Phys. B Proc. Suppl. **161** (2006), 136–152, [nucl-th/0511017]

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.

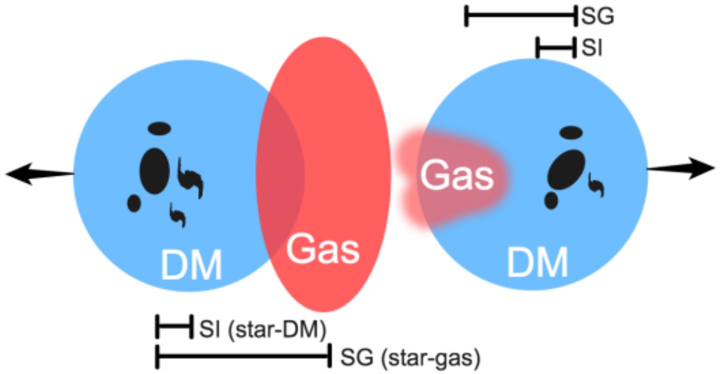
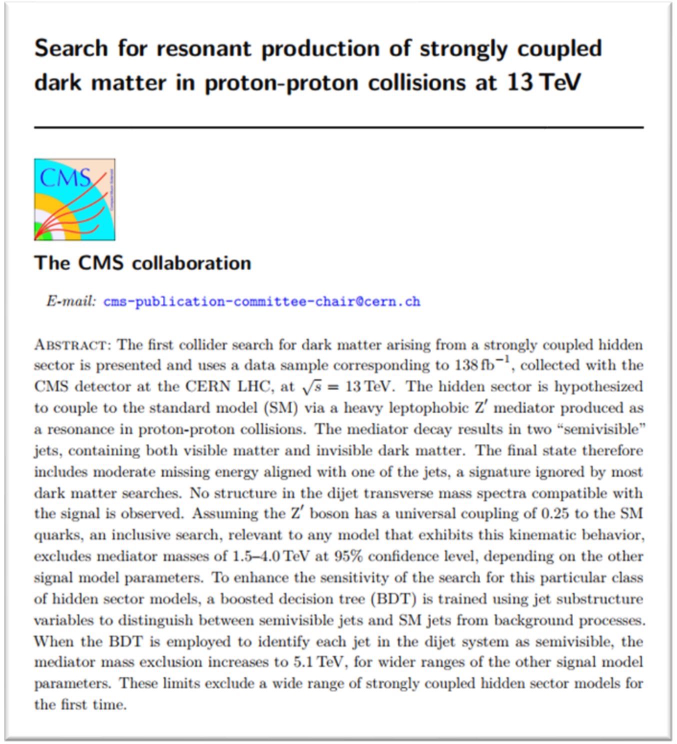


FIG. 1.— Schematic merger scenario: two subclusters have passed through each other, and the gas associated with each has slowed due to momentum exchange. This is observable as an offset between the star (i.e., galaxy) and gas positions, δ_{SG}. In analogy, any star-DM offset δ_{SI} may be attributed 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)



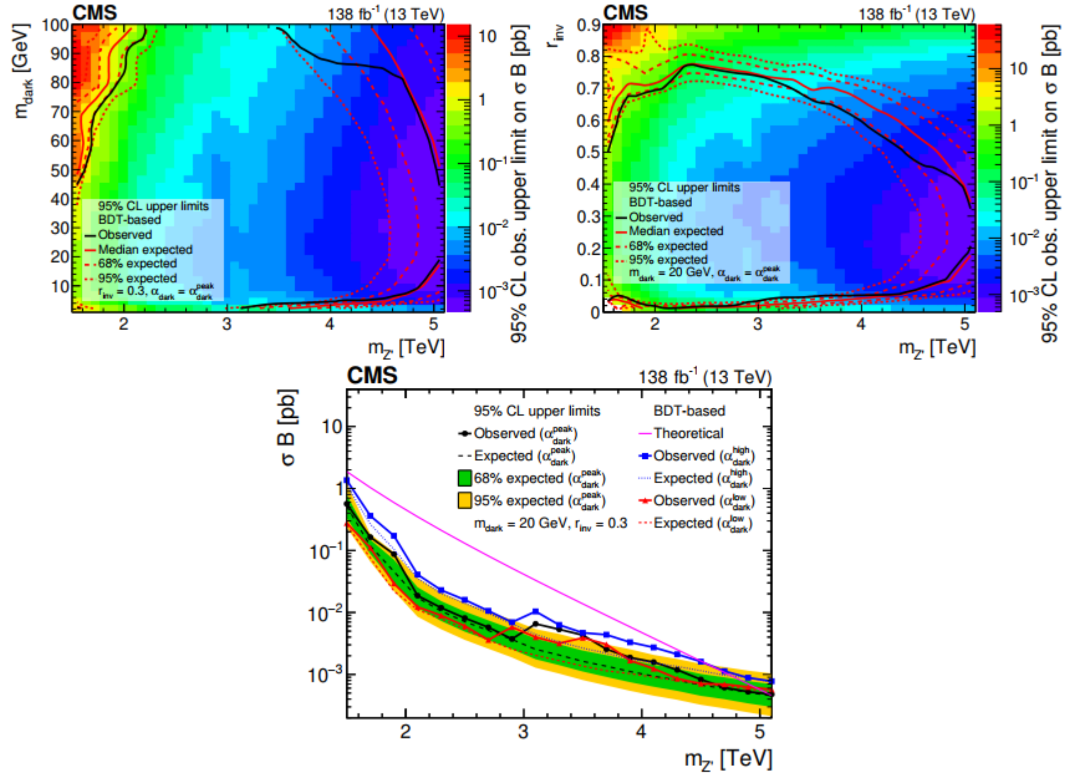
Search for resonant production of strongly coupled dark matter in proton-proton collisions at 13 TeV

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

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.

CMS Search



https://link.springer.com/article/10.1007/JHEP06(2022)156