Introduction to Searches in the Dark Sectors at Colliders

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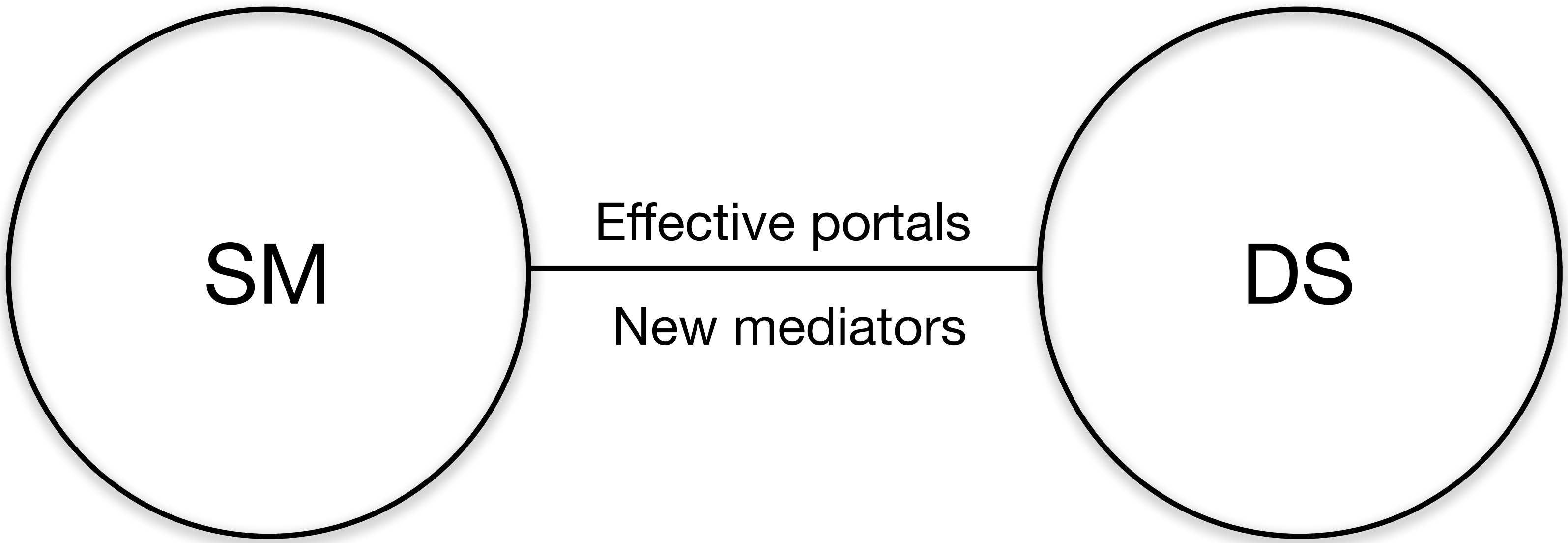
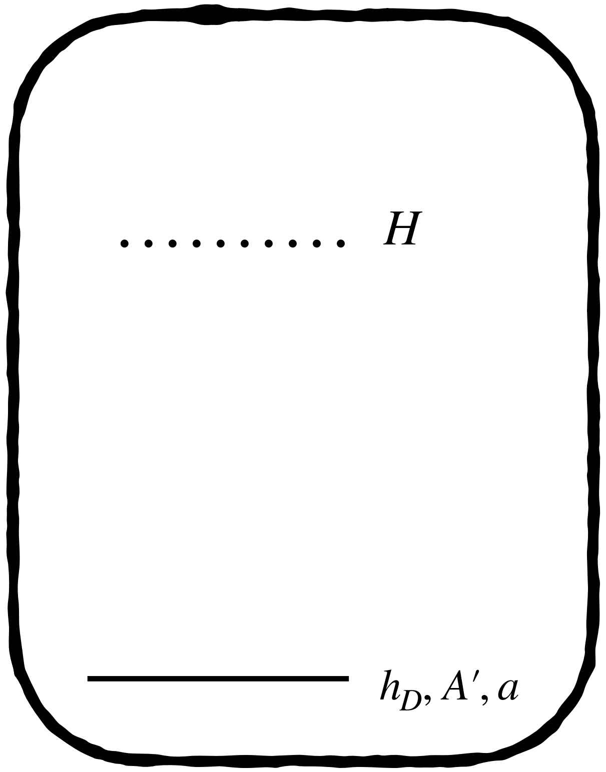
FWF Der Wissenschaftsfonds.

UNI GRAZ

Dark sectors at colliders

Strassler hep-ph/0604261





- New BSM sector although neutral under the SM may contain multiple particles
- Absence of mass-gap will lead to only missing energy signatures
- Mass-gap may lead to interesting signatures at colliders

Dark sectors at colliders

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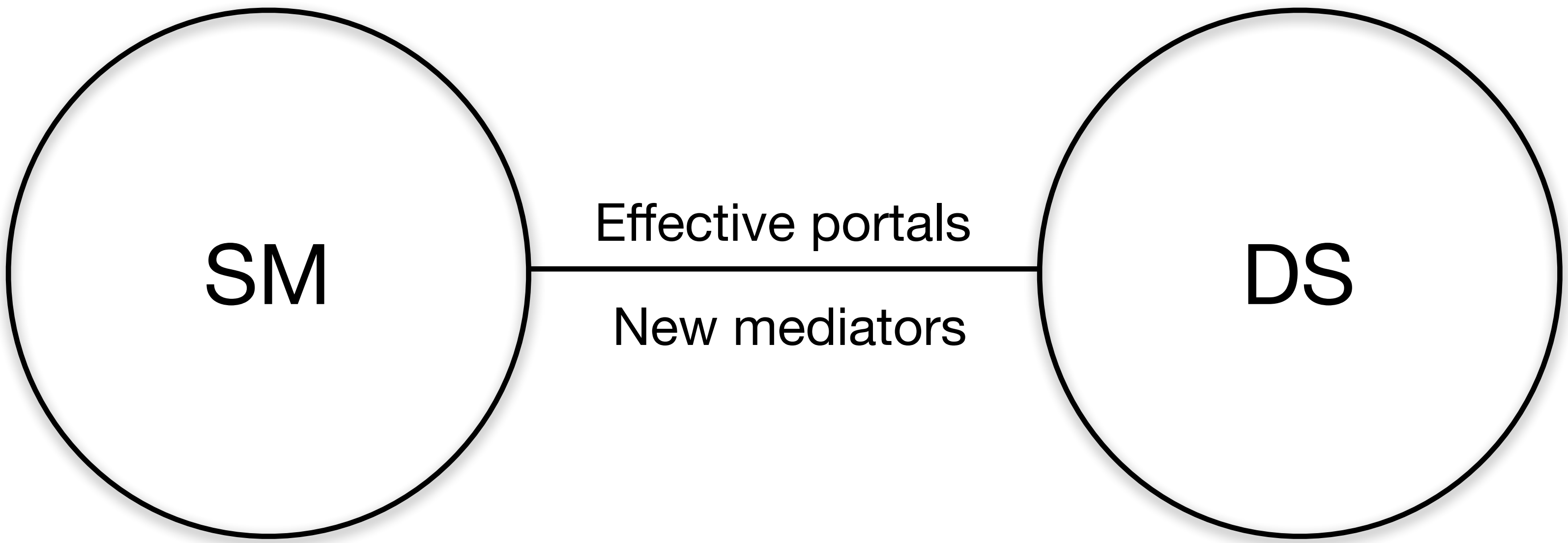

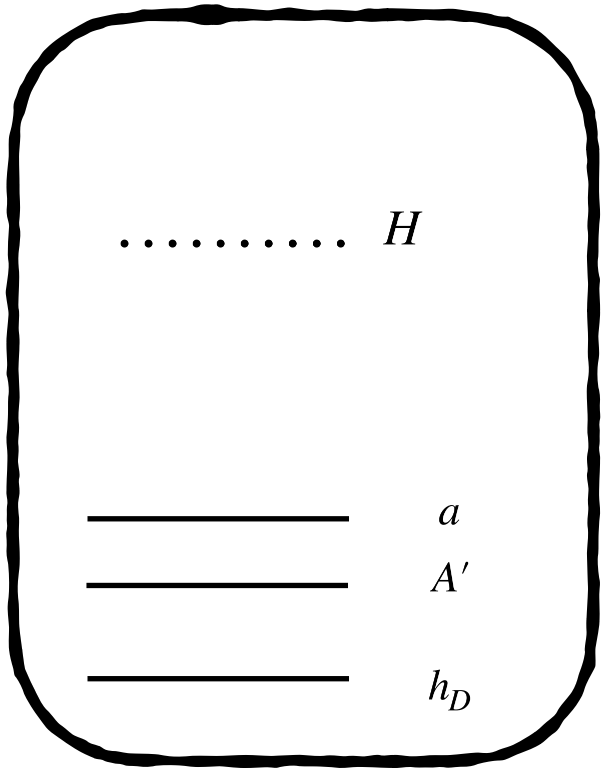

- New BSM sector although neutral under the SM may contain multiple particles
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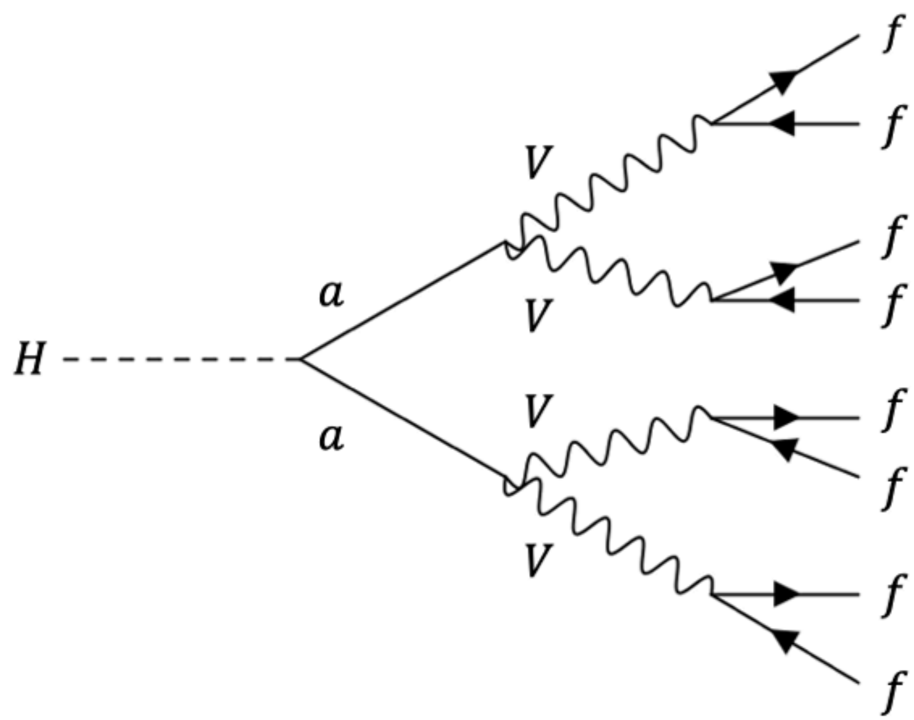
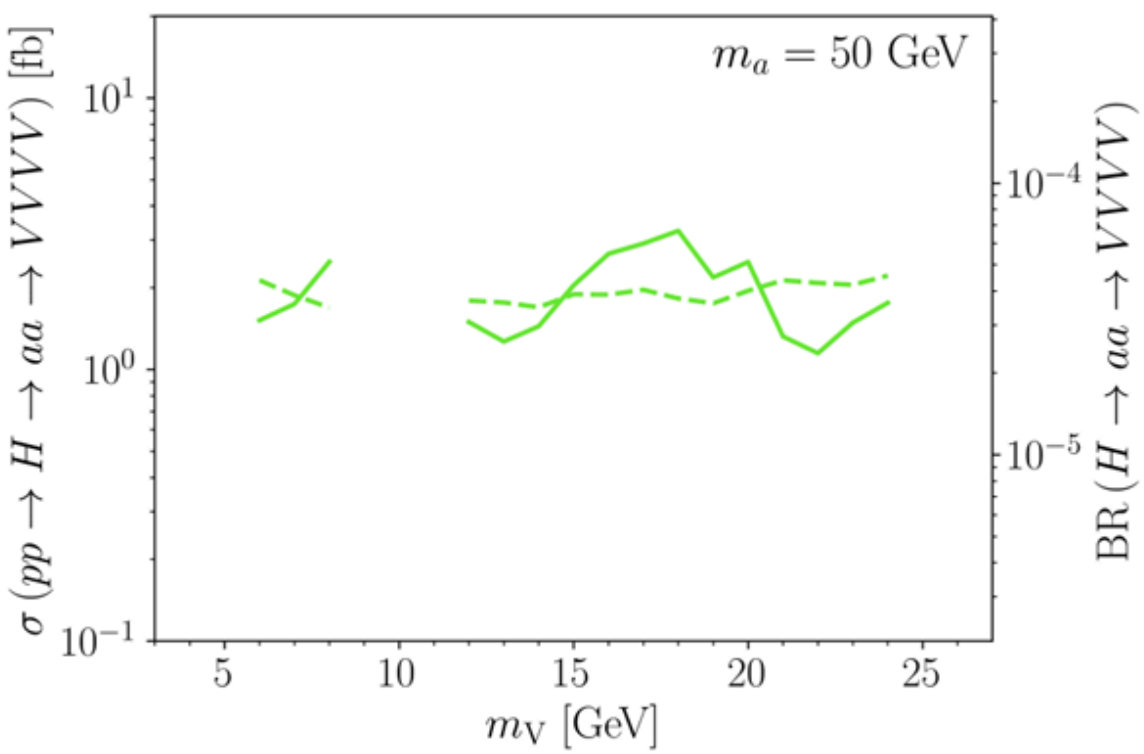
Dark sectors: example 1

Cheng, Husain, Li, Strassler
arXiv:2412.14452



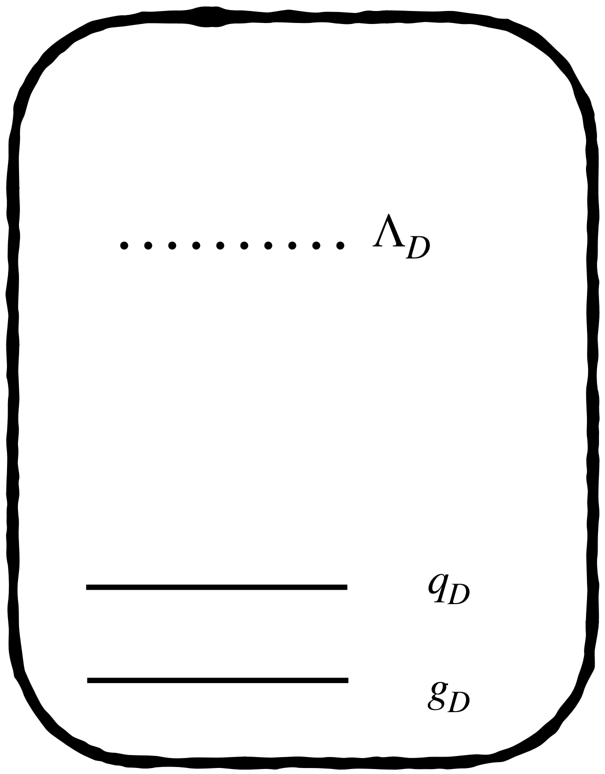


- Reinterpretation of ATLAS $Z \to 6f$ search
- Best limits on $BR(H \to aa \to VVVV) \sim 4 \times 10^{-5} - 1 \times 10^{-4}$
- Reusing existing searches is also a powerful strategy to constrain dark sectors
- This reinterpretation directly applicable to confining dark sectors/hidden valleys

Dark sectors with mass-gap

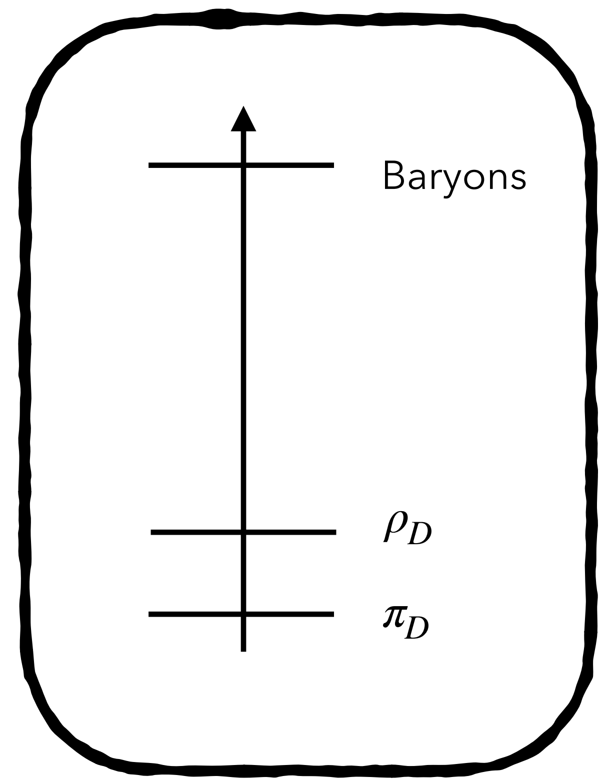
- Also known as dark-QCD or darkshowers/darkjets or hidden valleys

Strassler hep-ph/0604261

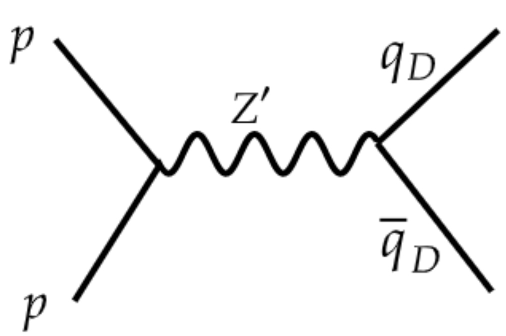


Low energy

χSB

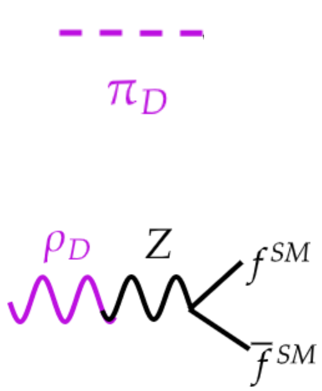


$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(N_C) \times U(1)_D$

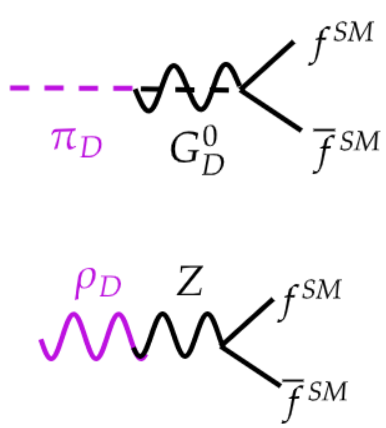


Low energy

Vector dark quarks



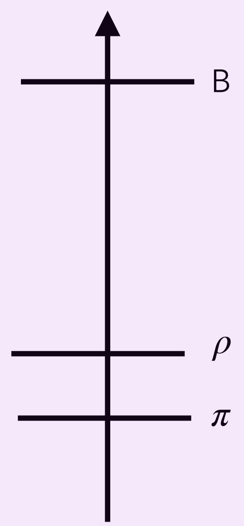
Chiral dark quarks



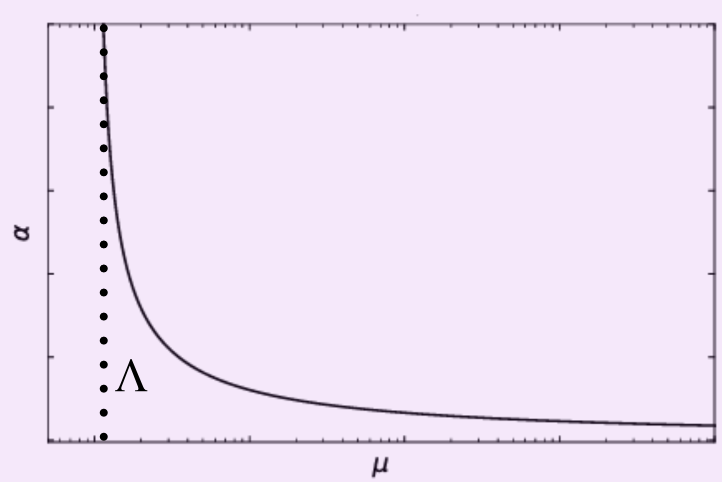
Hidden valleys characterisation

Asymptotically free

Spectrum

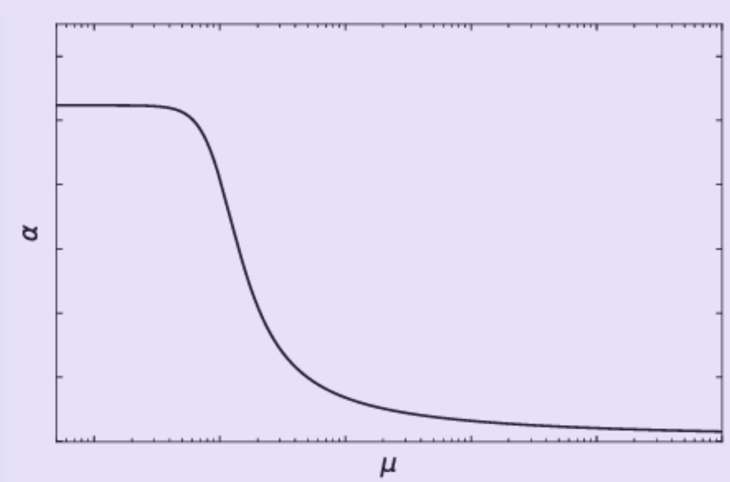


May form (dark) jets at the LHC



Two parameters $\Lambda, m_\pi/\Lambda$

- What is the exact value of $(N_F/N_C)_{CW}$?
- What are mass-gap generation mechanisms?
- What are the experimental signatures?



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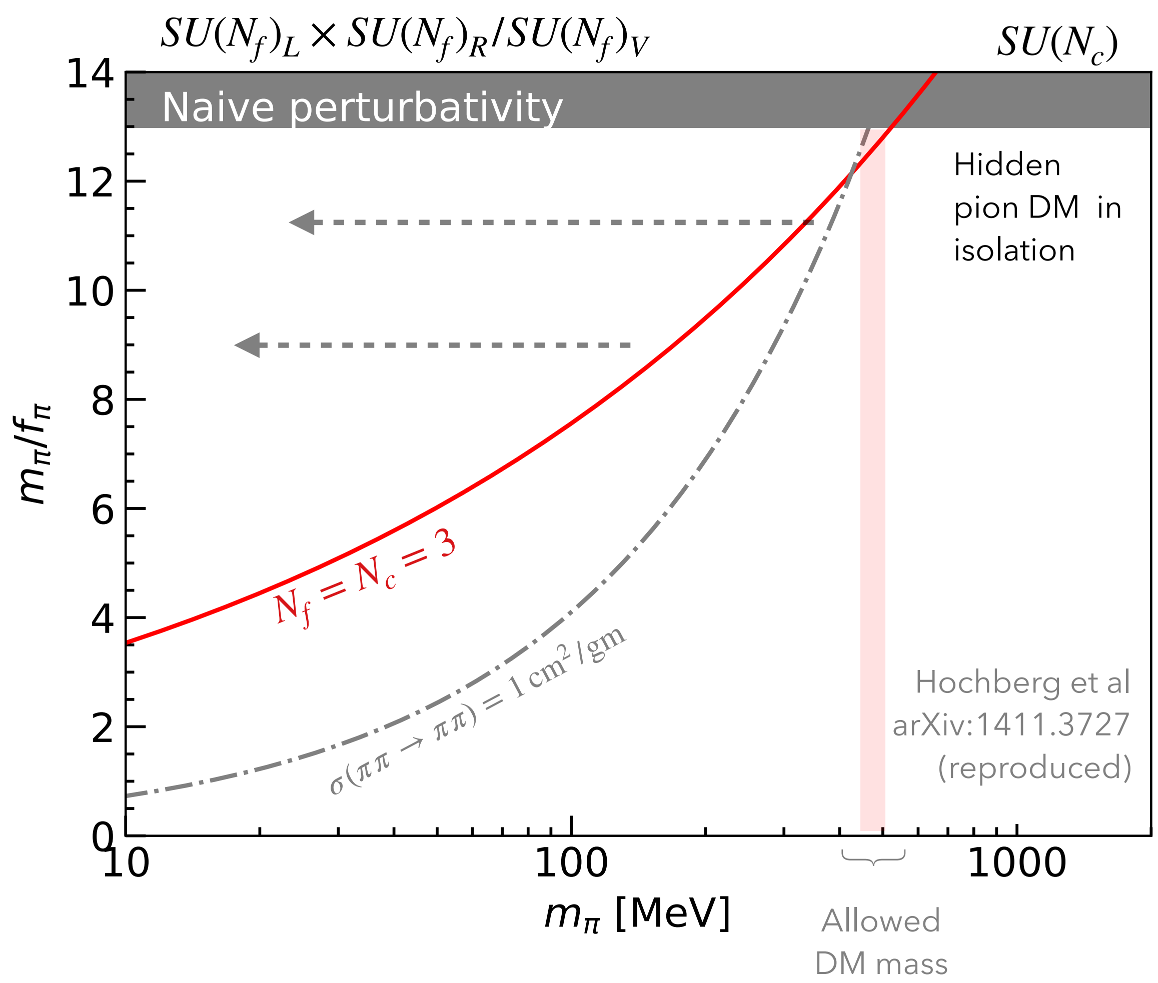
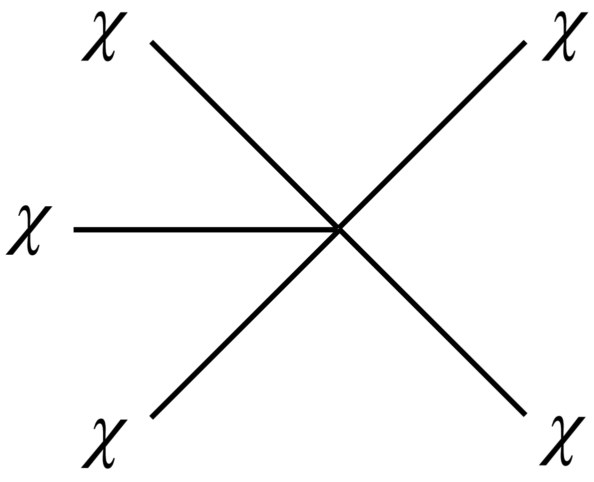
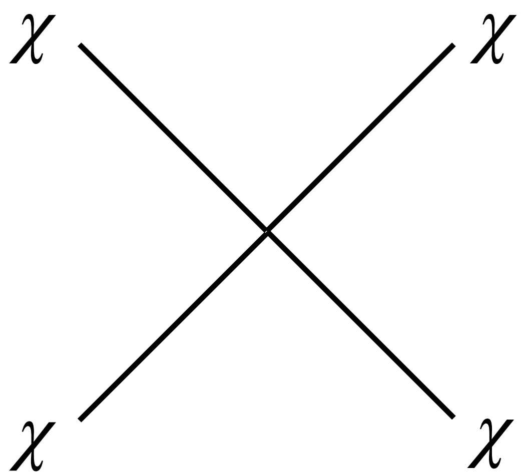
Current knowledge





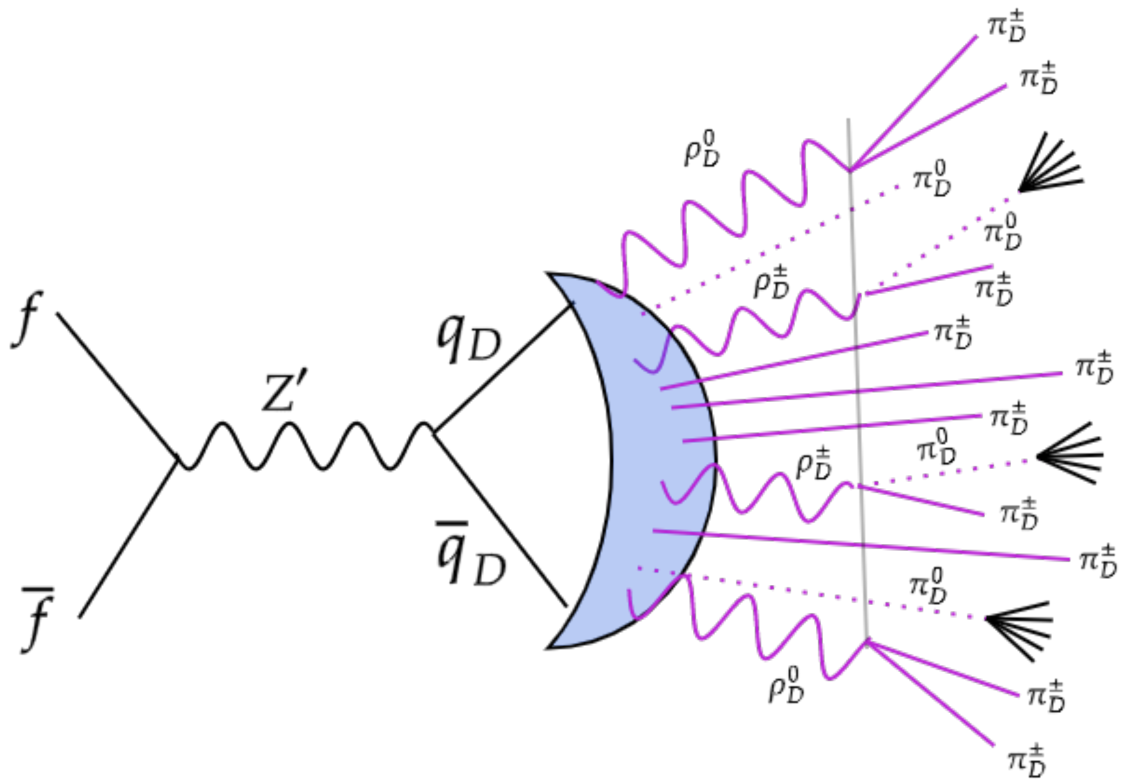
3 →2 annihilations

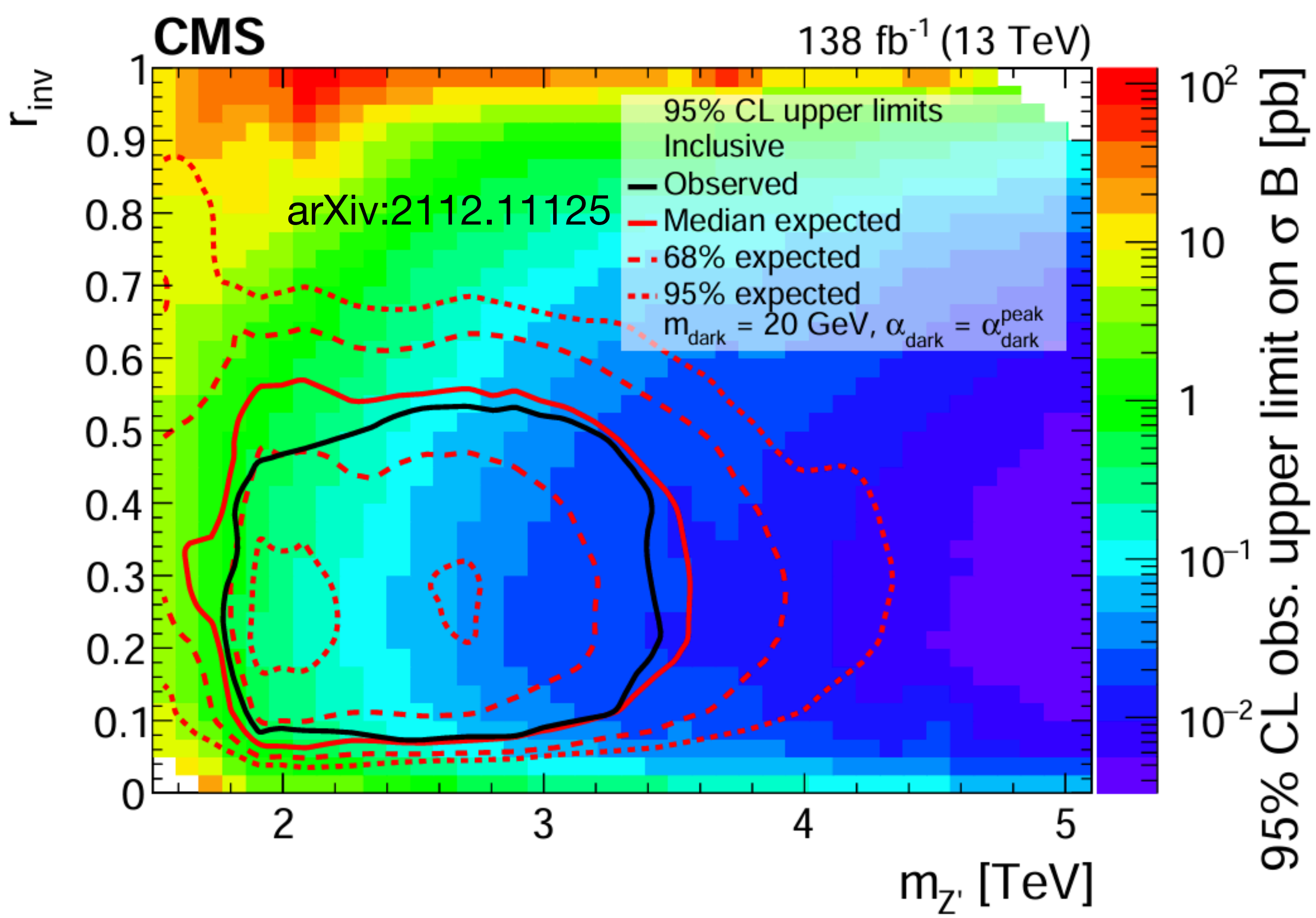


2 →2 self-interactions

- Needs pion masses $\mathcal{O}(100)\,\mathrm{MeV}$ to satisfy relic density and self-interactions
- Theory needs large m_π/f_π

Current knowledge

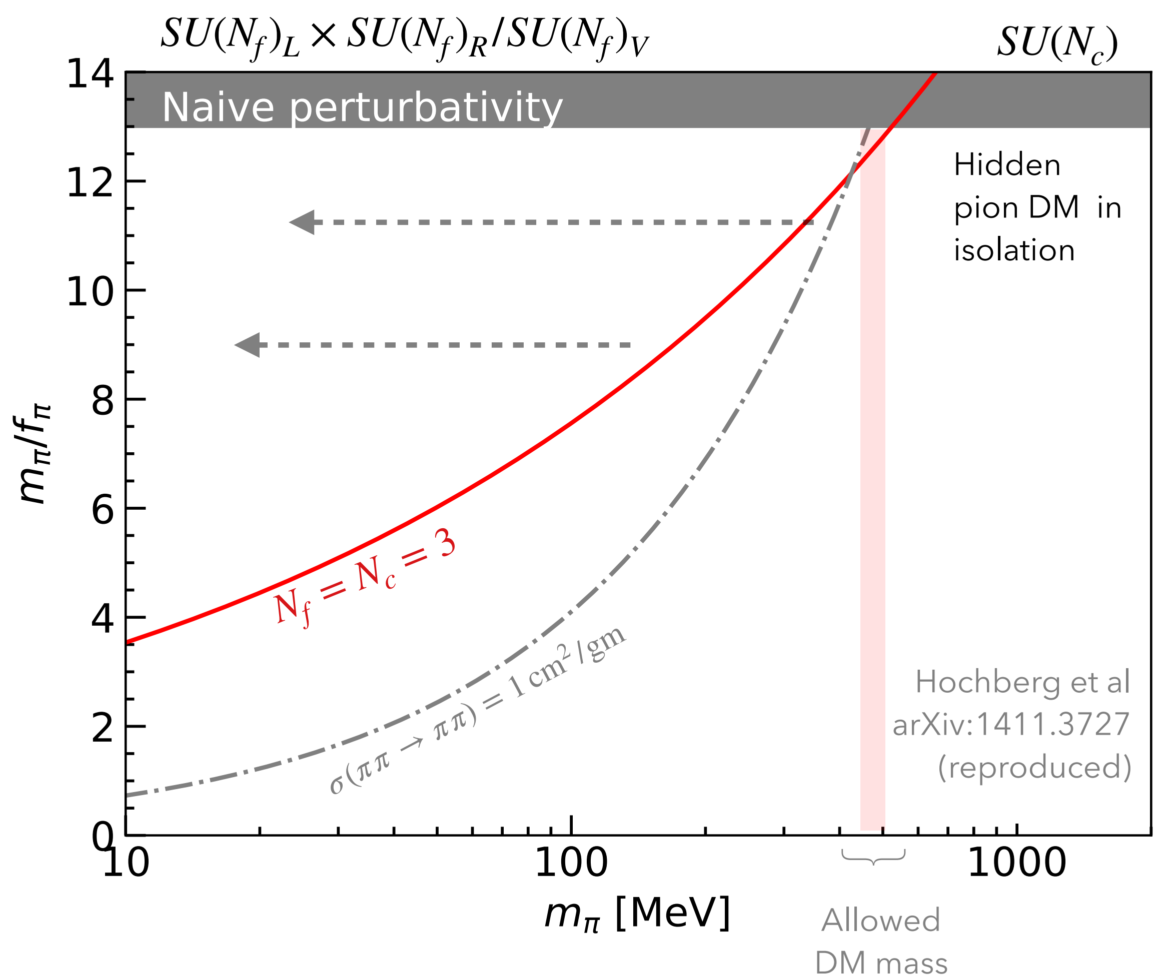


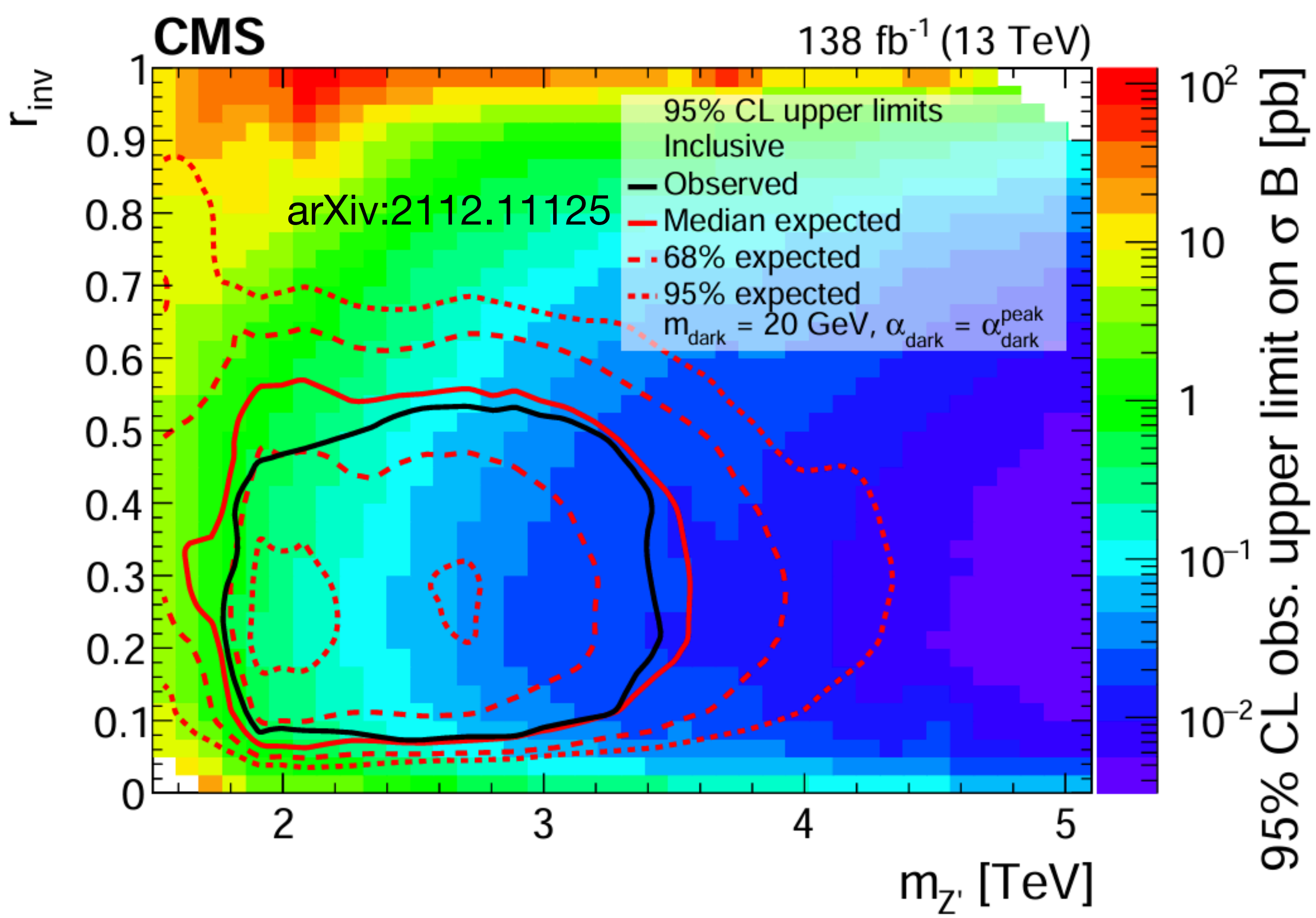


- Experimental searches characterise the theory space using some effective parameters which break UV-IR interplay

Current knowledge

Imperative to revisit both cosmological and experimental studies with detailed theory knowledge





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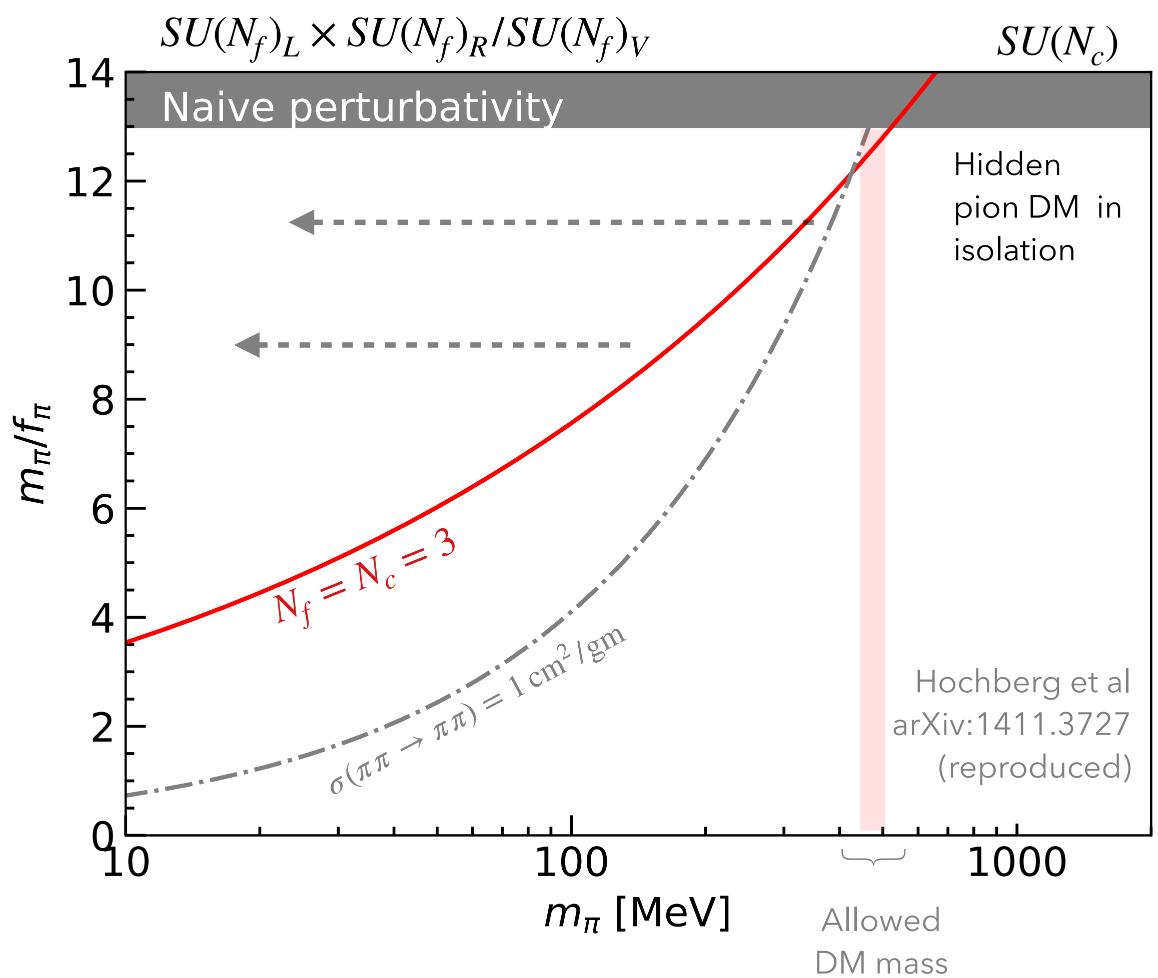
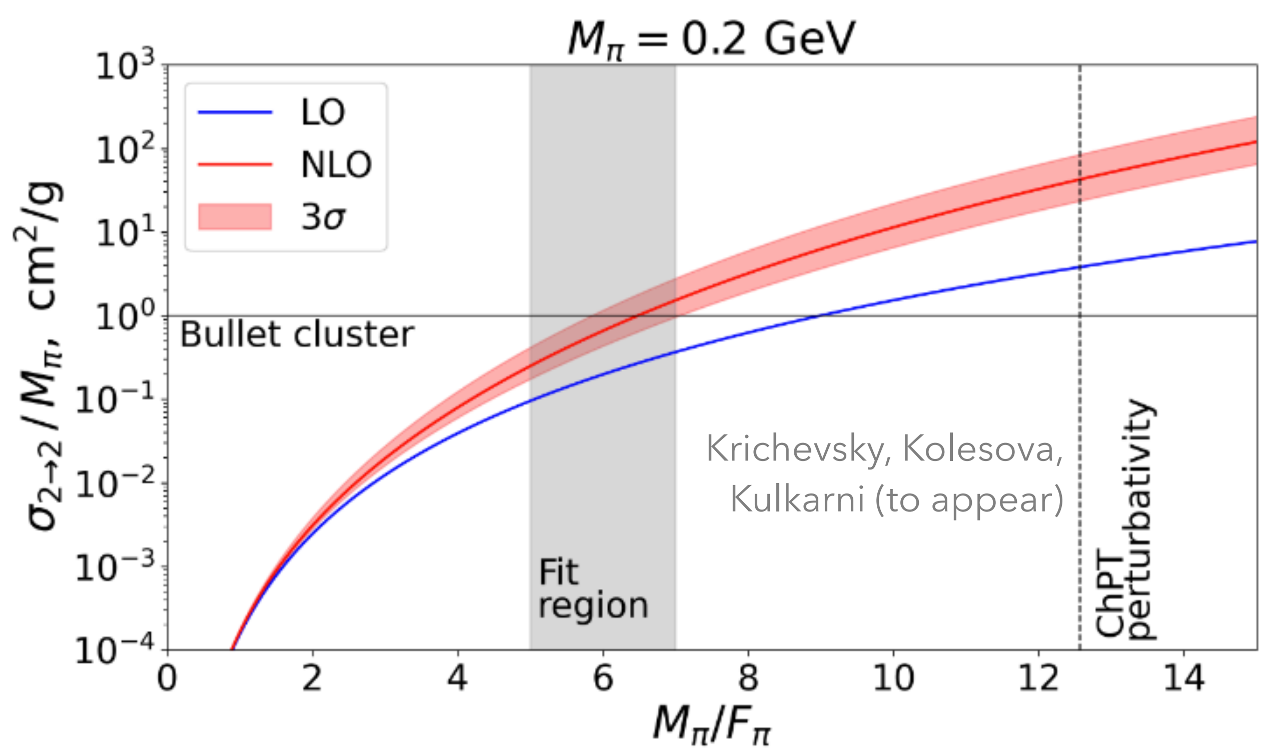
NLO effects





- Needs pion masses $\mathcal{O}(100)\,\mathrm{MeV}$ to satisfy relic density and self-interactions
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- NLO corrections to pion self-scattering are very large potentially questioning the validity of interesting pion dark matter regimes

See also Hansen et al. arXiv:1507.01590

NLO effects

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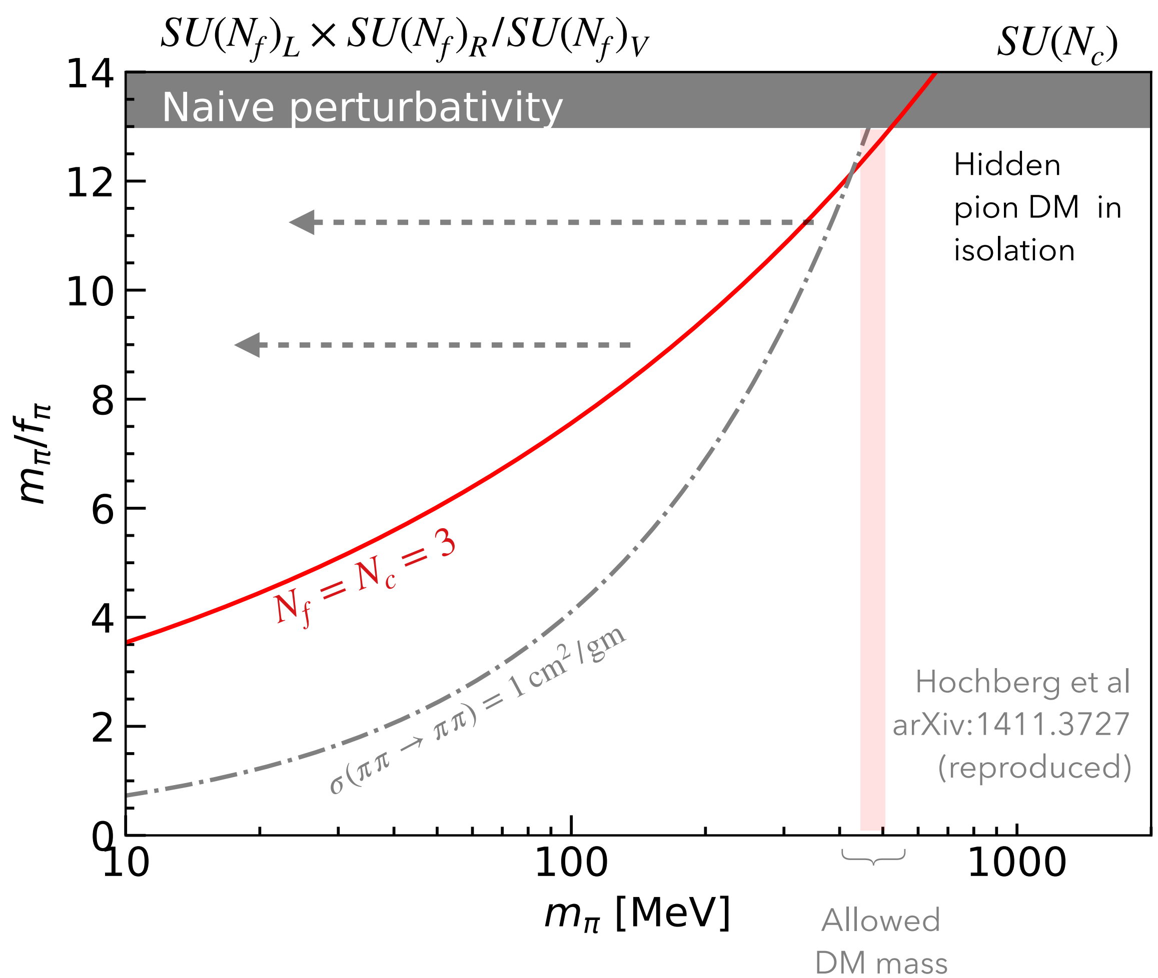

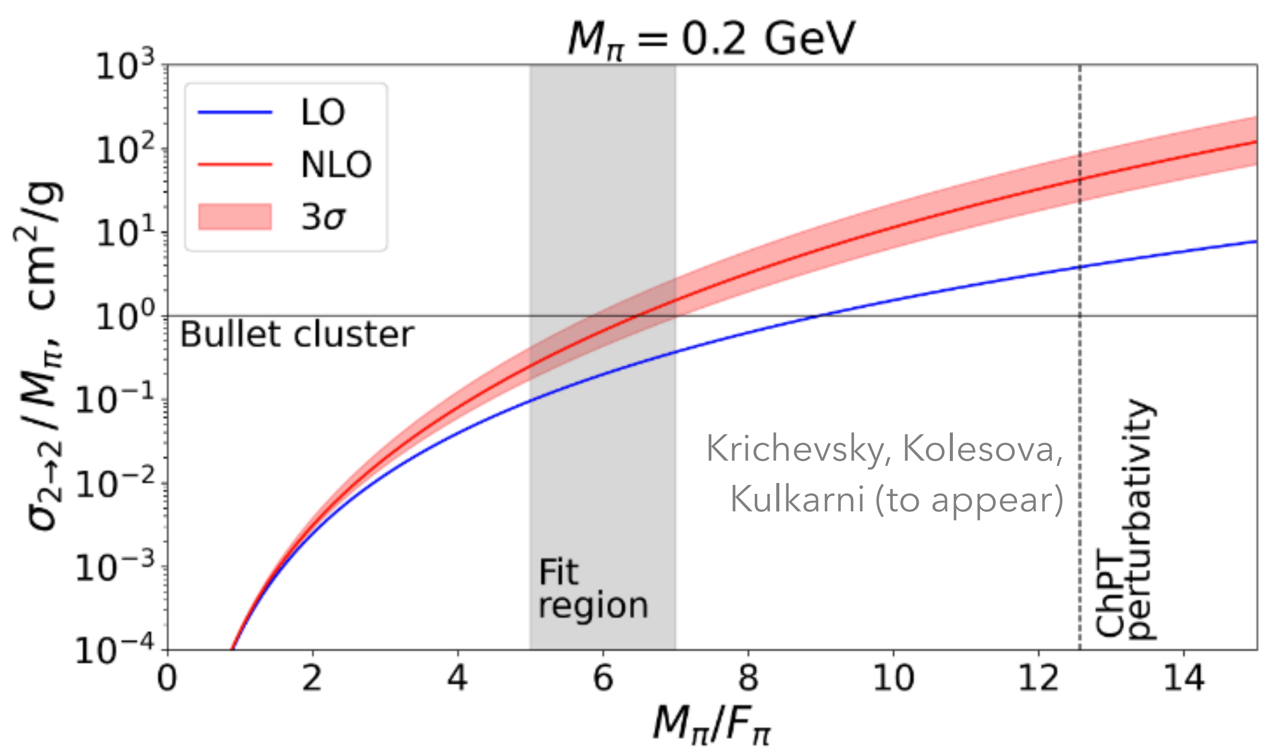

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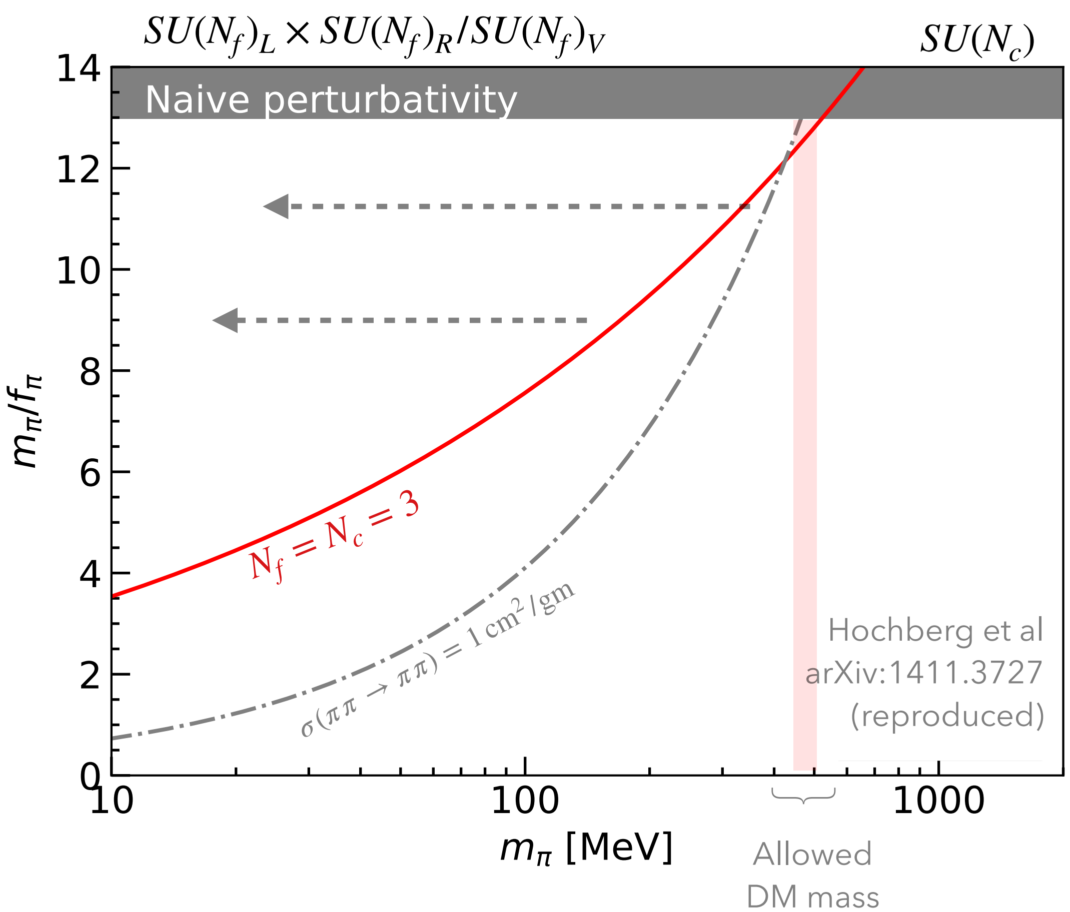
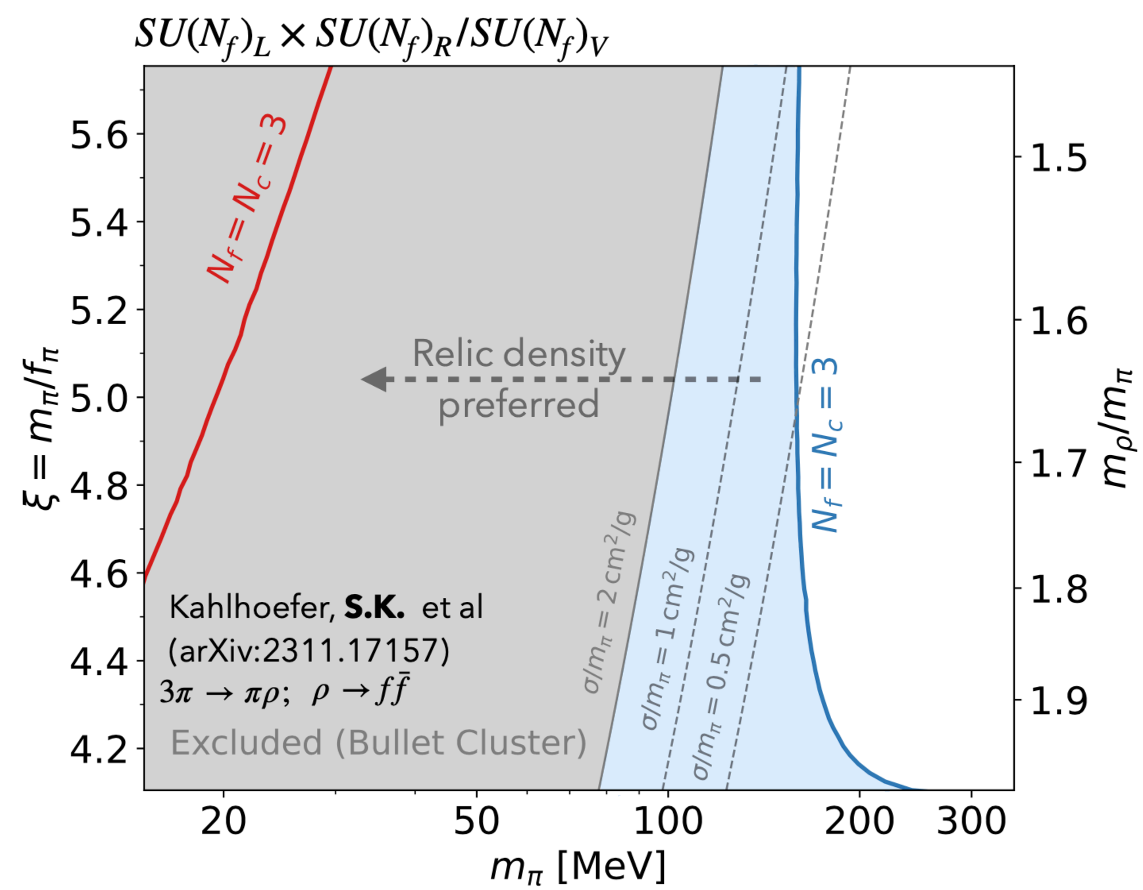
Dark sectors 1: dark matter

Hochberg et al arXiv:1411.3727, 1512.07917, Hansen et al arXiv:1507.01590, Heikinheimo arXiv:1803.07518, Cline et al arXiv:2108.10314, Braat et al arXiv: 2301.04513, Kamada et al arXiv:2304.12621, Choi et. al. arXiv:1801.07726, Berlin et al arXiv:1801.05805, Kahlhoefer et al arXiv:1907.04346

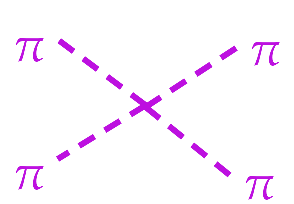
Non-perturbative inputs make a big difference to DM; properties of heavier states are important

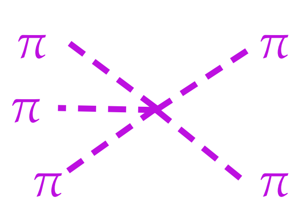
- Astrophysical observations fix the scale of the theory

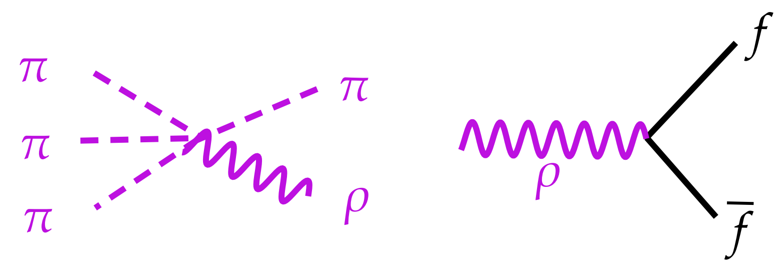




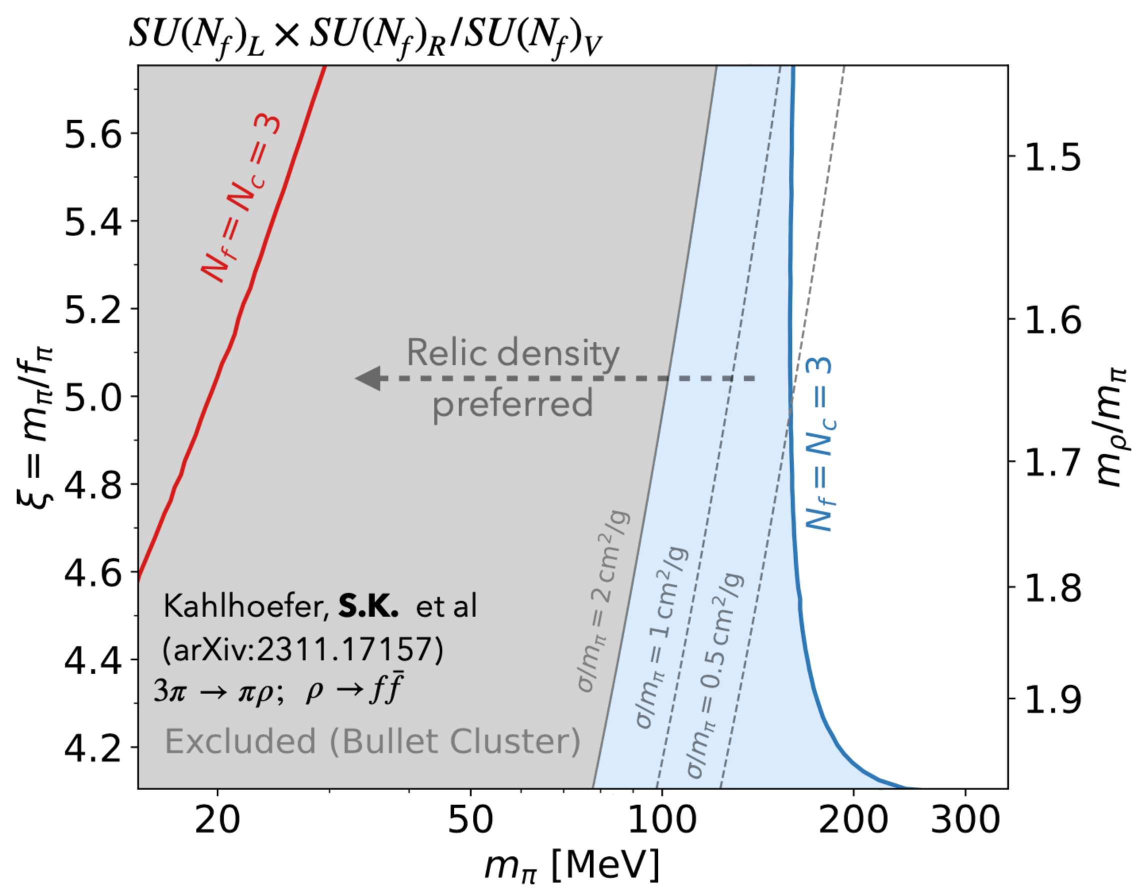
$$\mathscr{L} = \mathscr{L}_{\text{non-anom}} + \mathscr{L}_{\text{anom}}$$



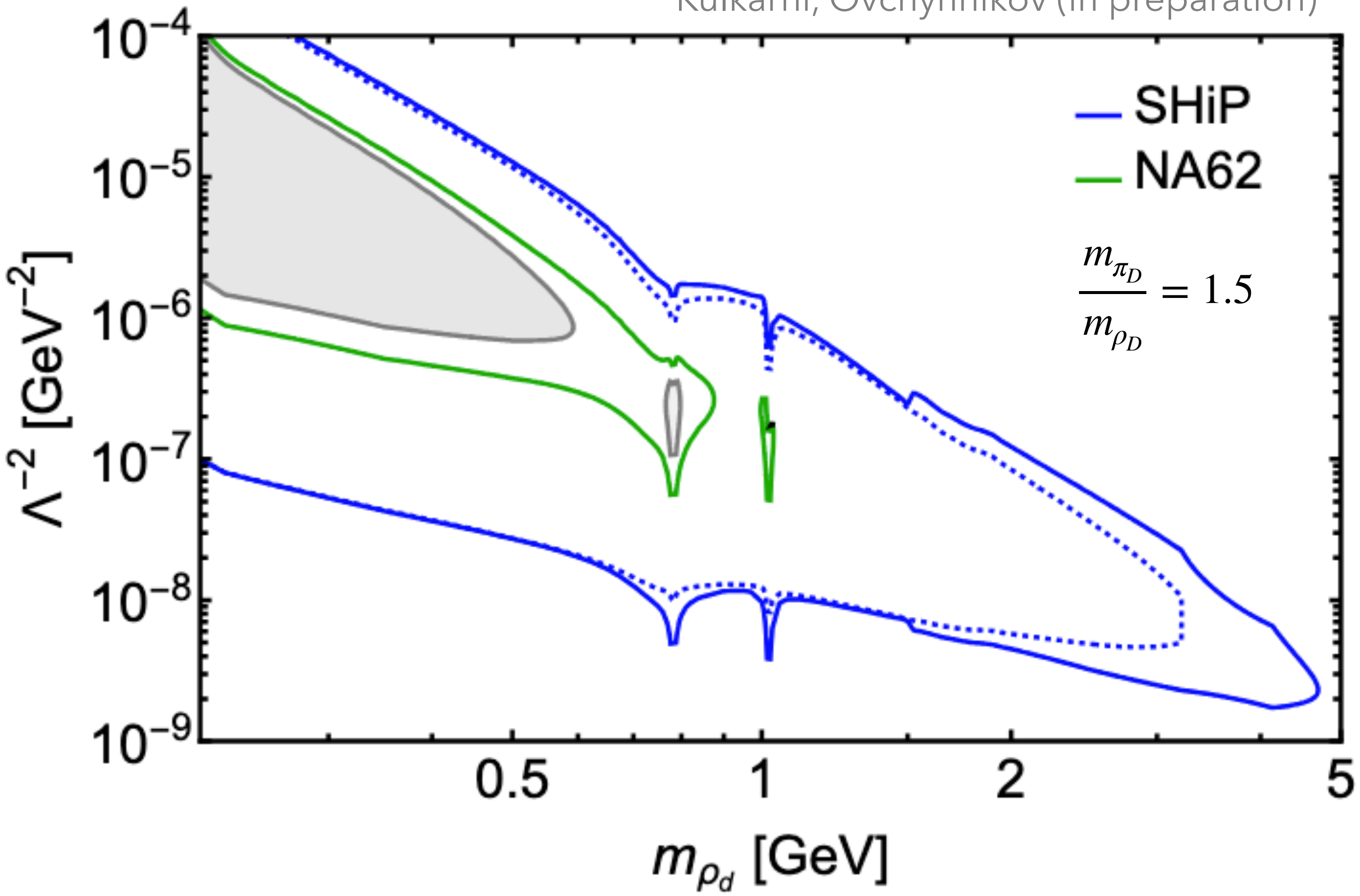




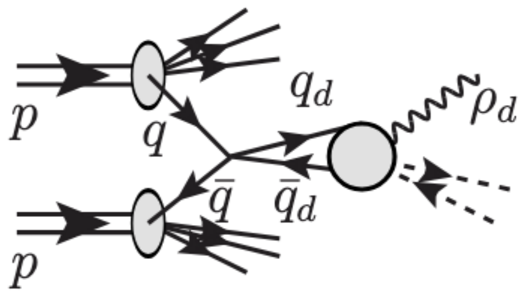
Dark sectors 1: dark matter



Bernreuther, Hemme, Kahlhoefer, Kulkarni, Ovchynnikov (in preparation)



- Λ: strength of SM - dark quark effective coupling
- "Darkshowers" are not limited to high energy colliders
- SHiP has excellent prospects to probe the light dark mesons useful for dark matter phenomenology

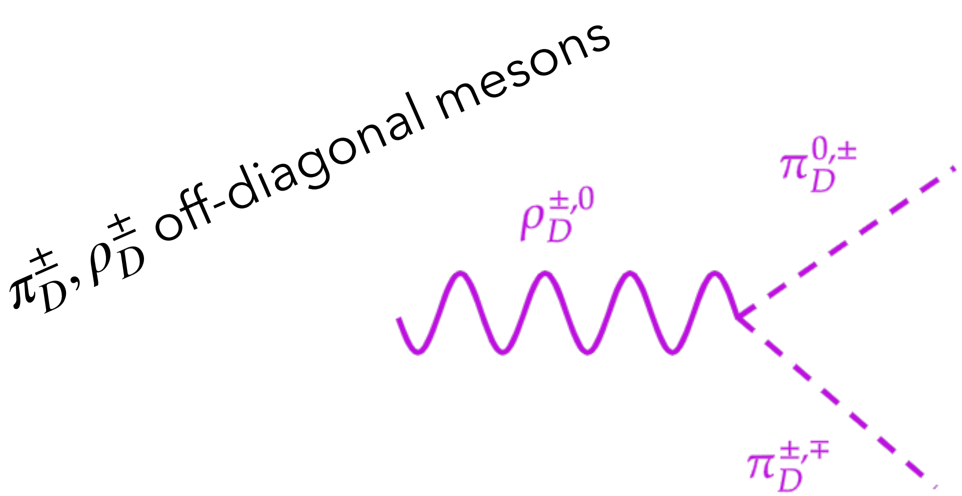


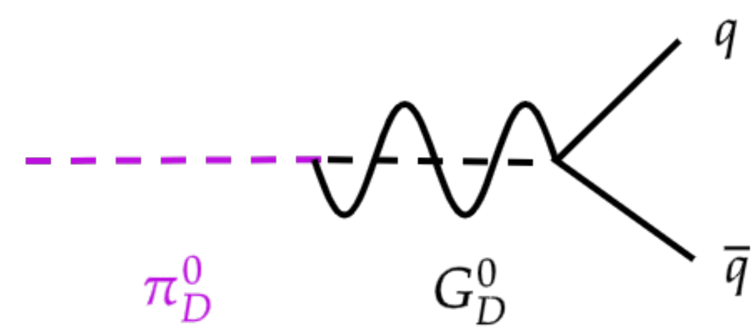
Dark sectors 2: experimental signatures

Why should we adhere to theory guidelines for experimental searches?

Liu, Lockyer, Kulkarni (arXiv:2505.03058)

- Consider theories containing chiral dark quark





- Theory contains $N_F^2 - 1$ total pions, one spin-0 flavour singlet and N_F diagonal pions (including η_D); similarly the rho mesons
- Let us only consider situations when all (N_F) diagonal pions decay
- These dark pions will be long lived particles because Z_D is heavy

Dark sectors 2: experimental signatures

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Xiv:2505.03058)

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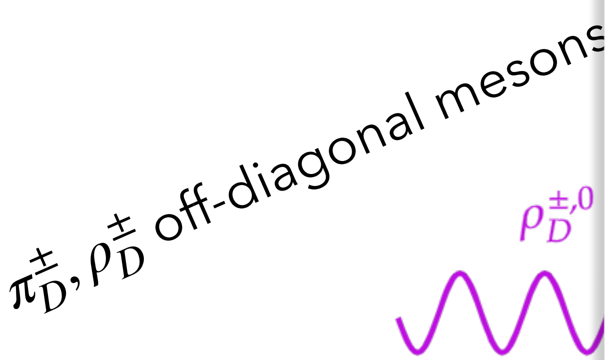

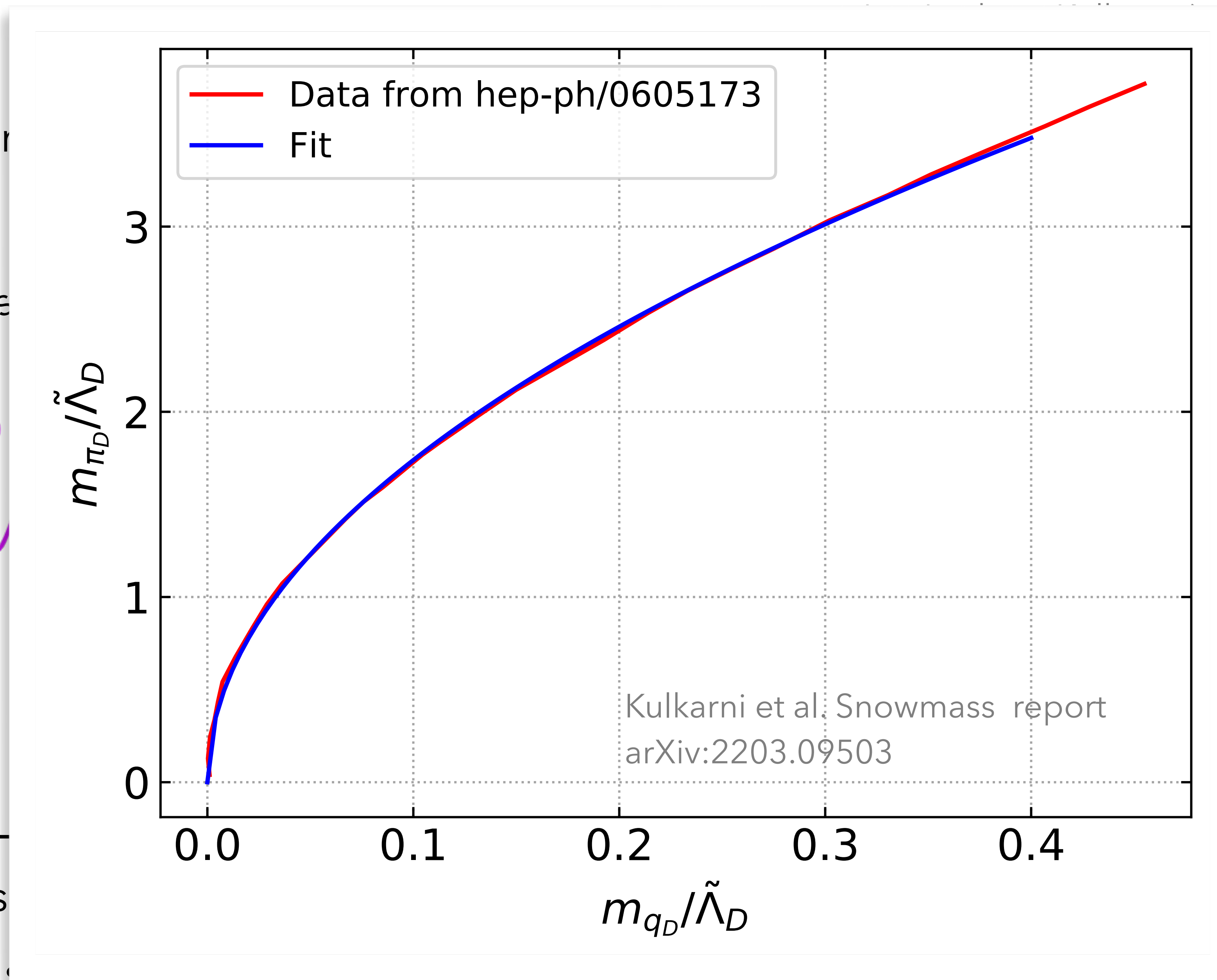

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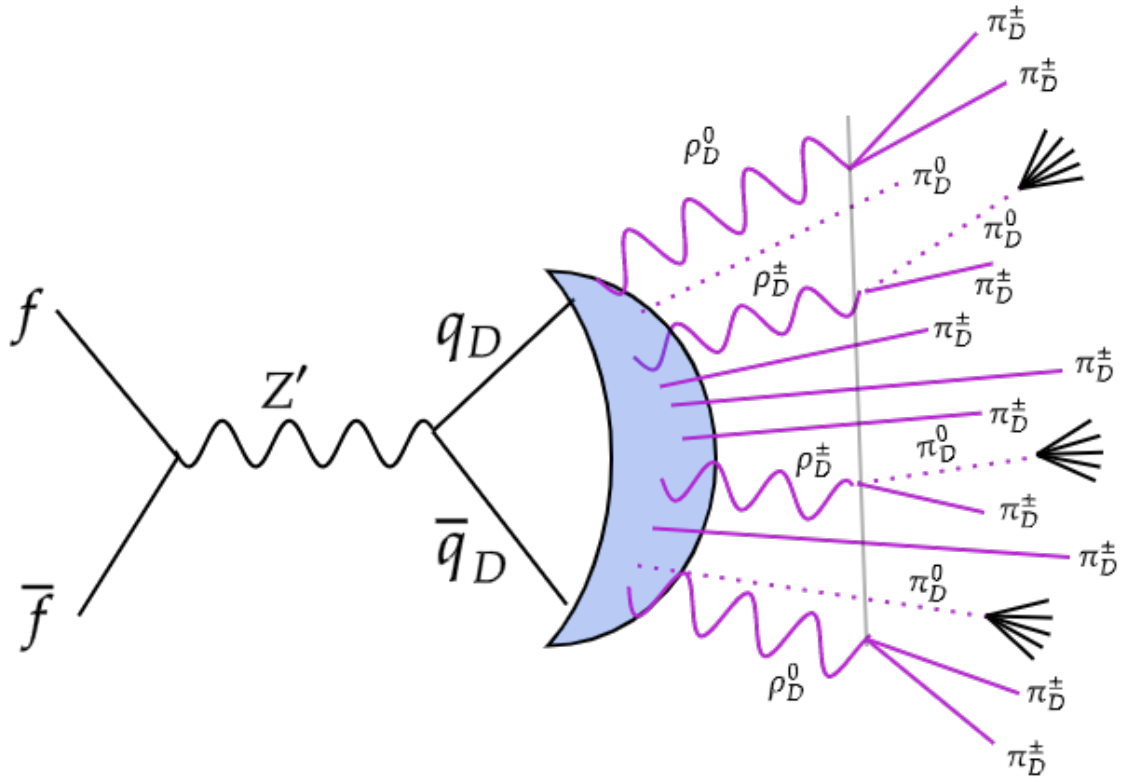
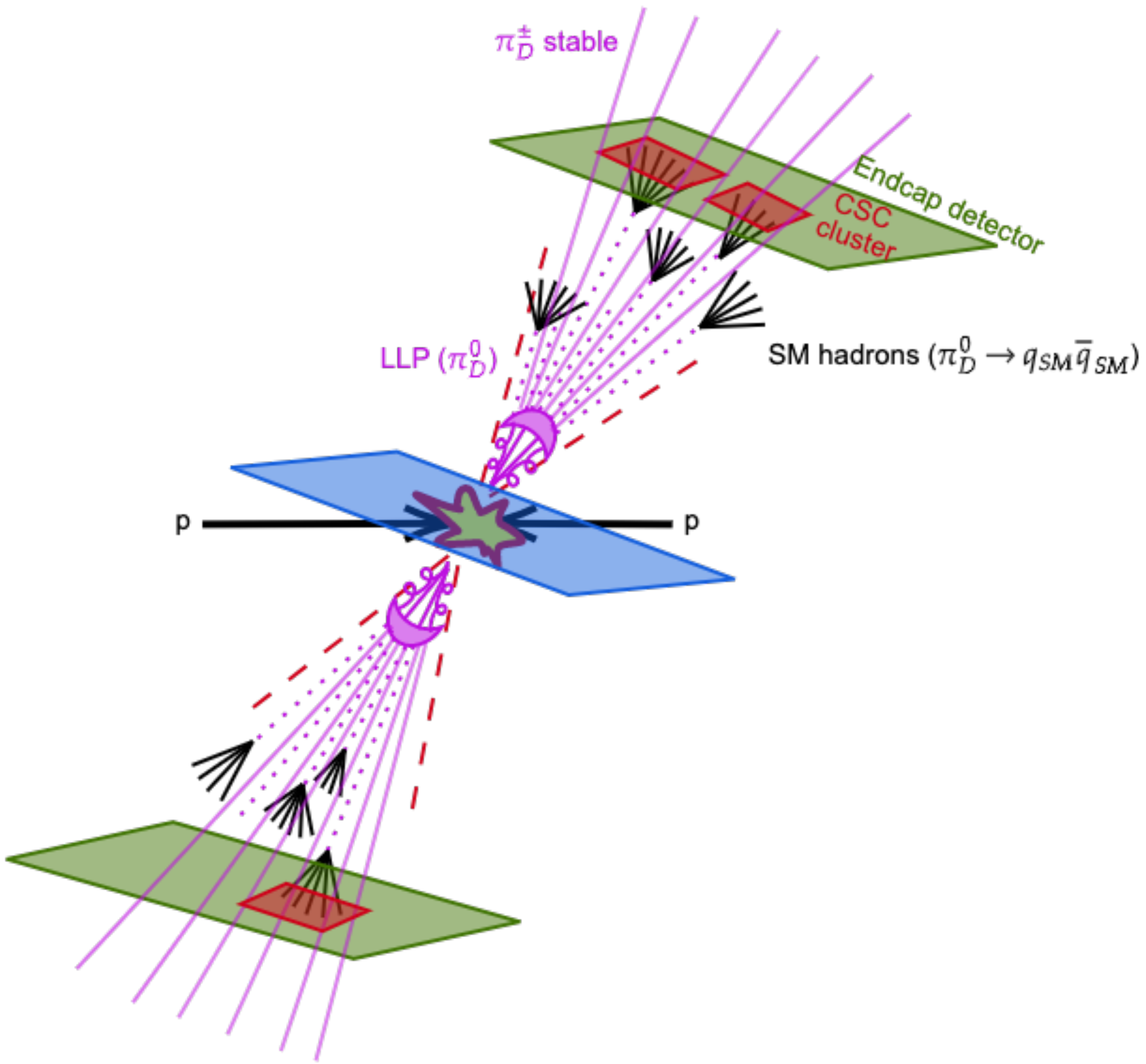
Darkshowers in CMS muon detector





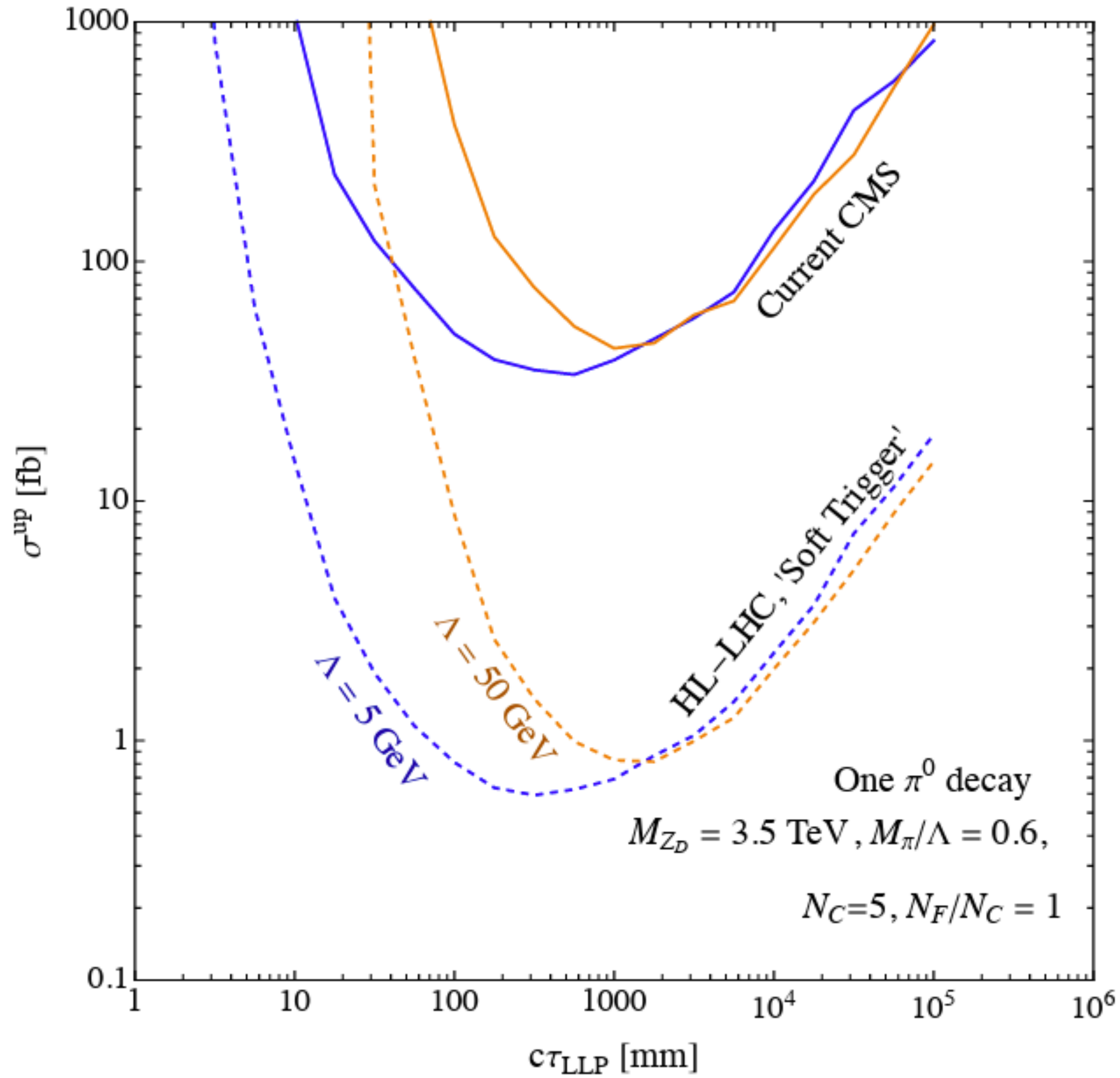
- Three different details matter:
  - Dark hadron mass spectrum
  - Dark hadron decays
  - Dark shower and hadronization
- Dark shower is controlled by $m_{Z'}/\Lambda_D$
- Dark hadronization is still an open question

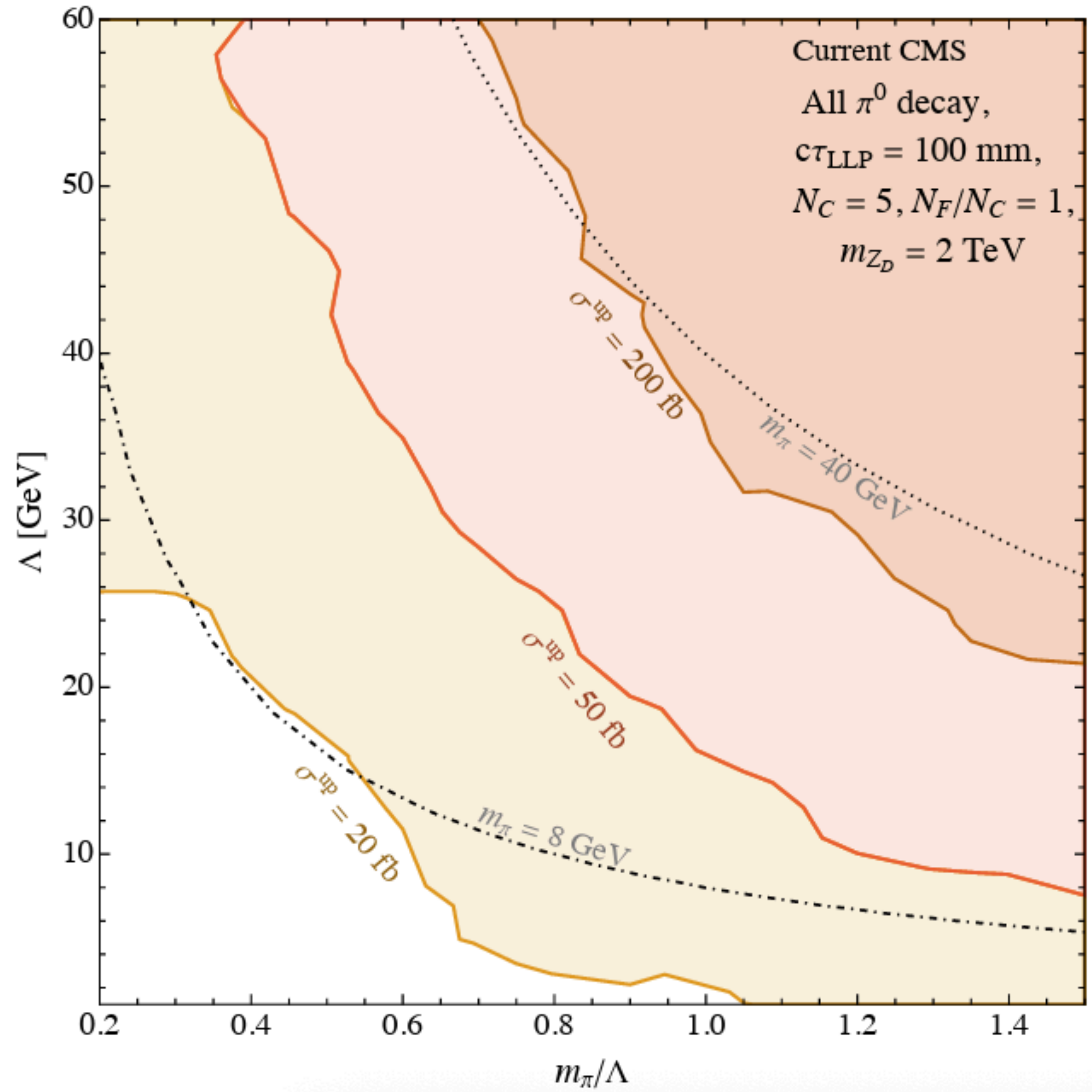
- N.B. The LLP multiplicity is very important

First limits on hidden valley dark sectors

Theoretically consistent setup leads to more in depth knowledge for experimental signatures

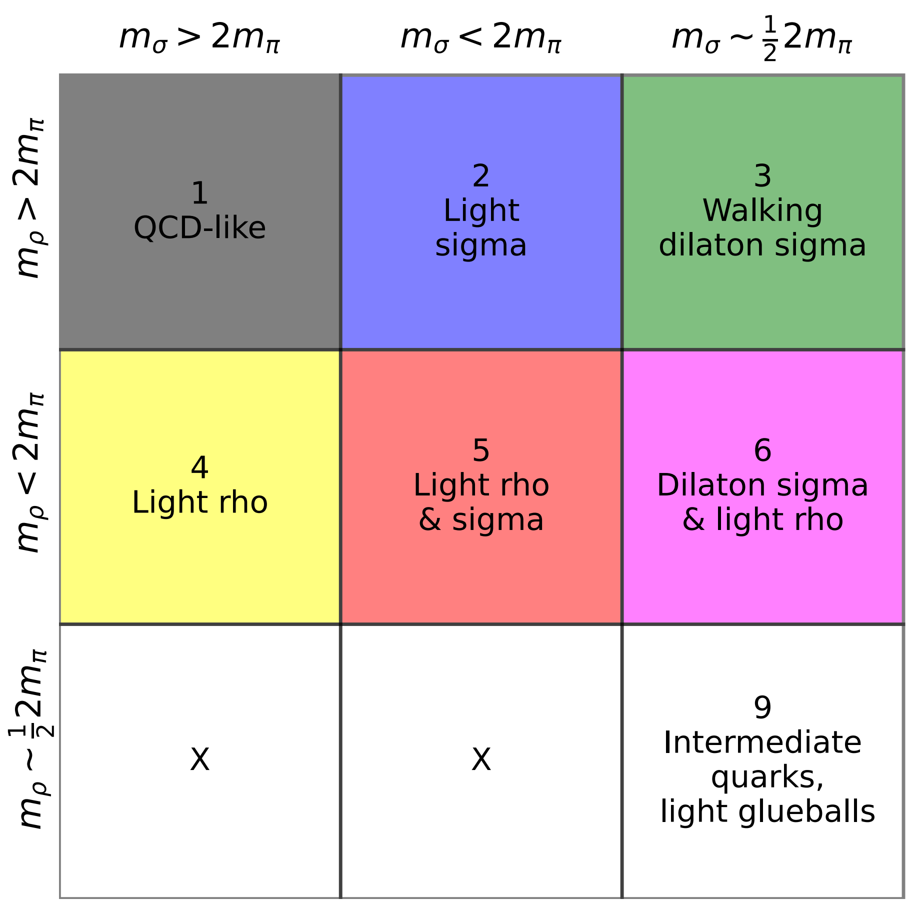
Liu, Lockyer, Kulkarni (arXiv:2505.03058)

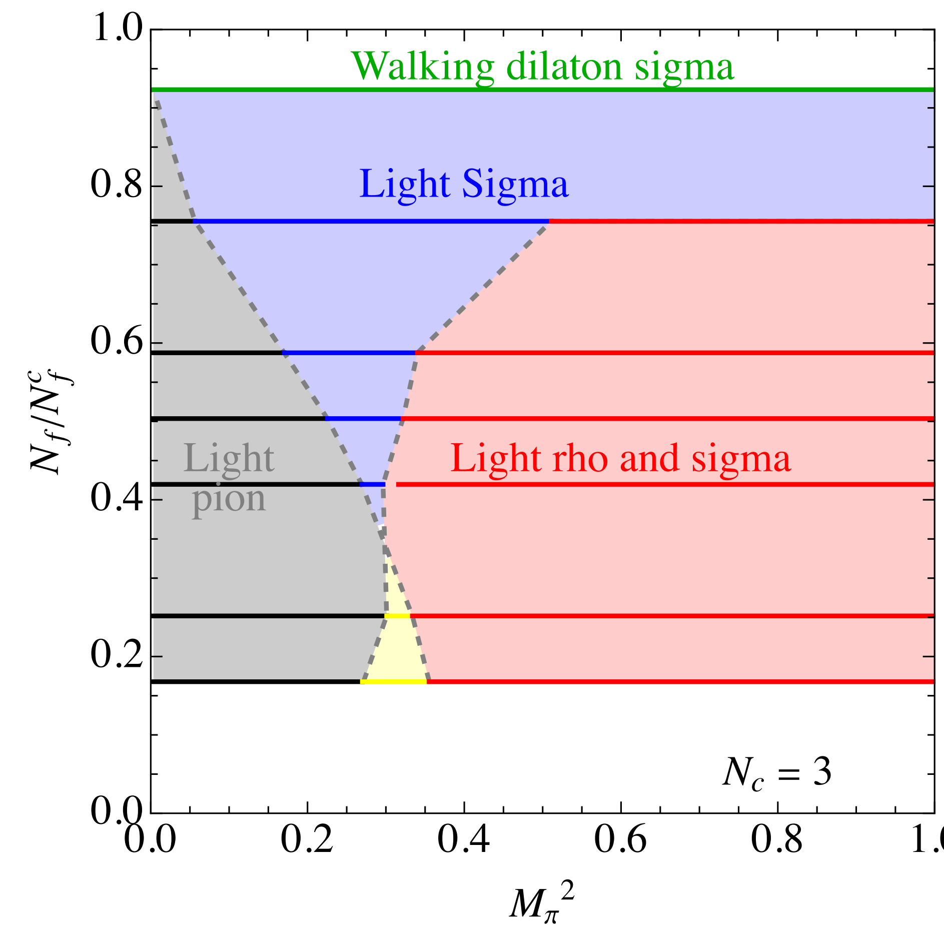




Survey of hidden valley dark sectors

Alfano, Evans, Kulkarni, Porod (to appear)





- Actual mass spectrum of chirally broken confining dark sectors is complex
- Holography studies provide useful guidance to understand spectral features
- Complex final states are to be expected

Dark sectors 3: Going beyond QCD-like theories

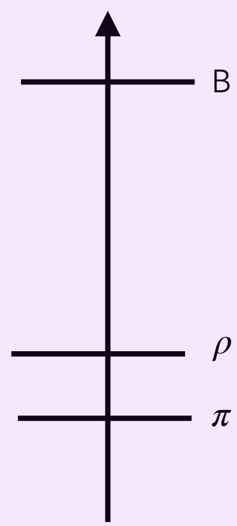
Kulkarni, Lockyer, Strassler (arXiv:2502.18566)

Asymptotically free

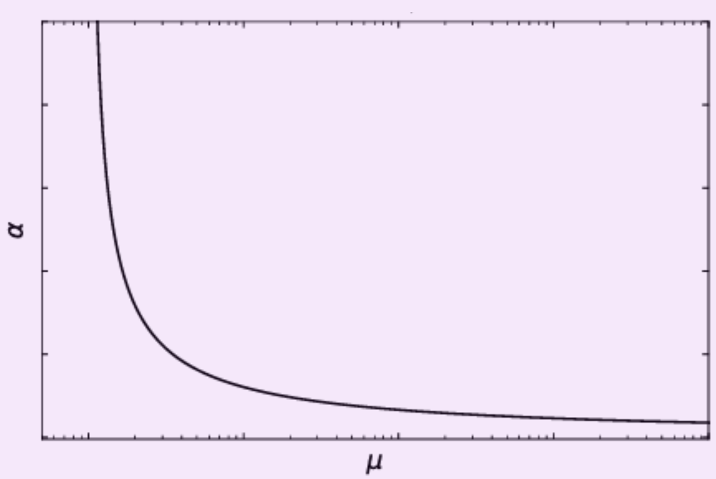
QCD-like (QL) | Conformal window (CW) | Infrared free (IF)

0 | $(N_F/N_C)_{CW}$ | $11/2$ | N_F/N_C

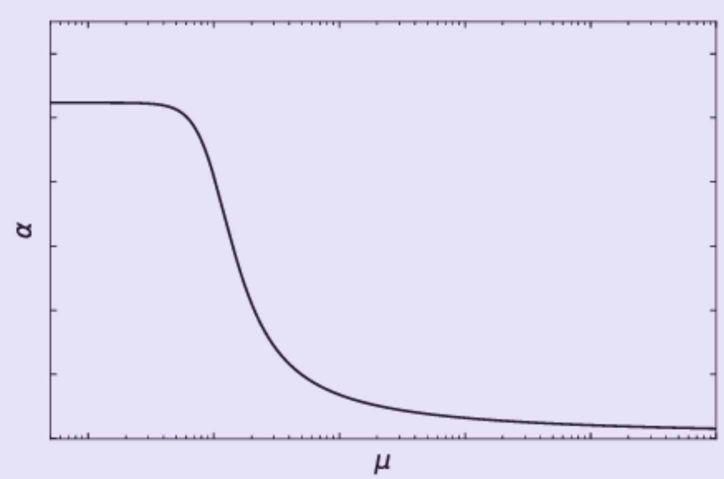
Spectrum



May form (dark) jets at the LHC



- What is the exact value of $(N_F/N_C)_{CW}$?
- Do bound states exist?
- What are the experimental signatures?
- Are they always conformally invariant? (Scale invariant?)



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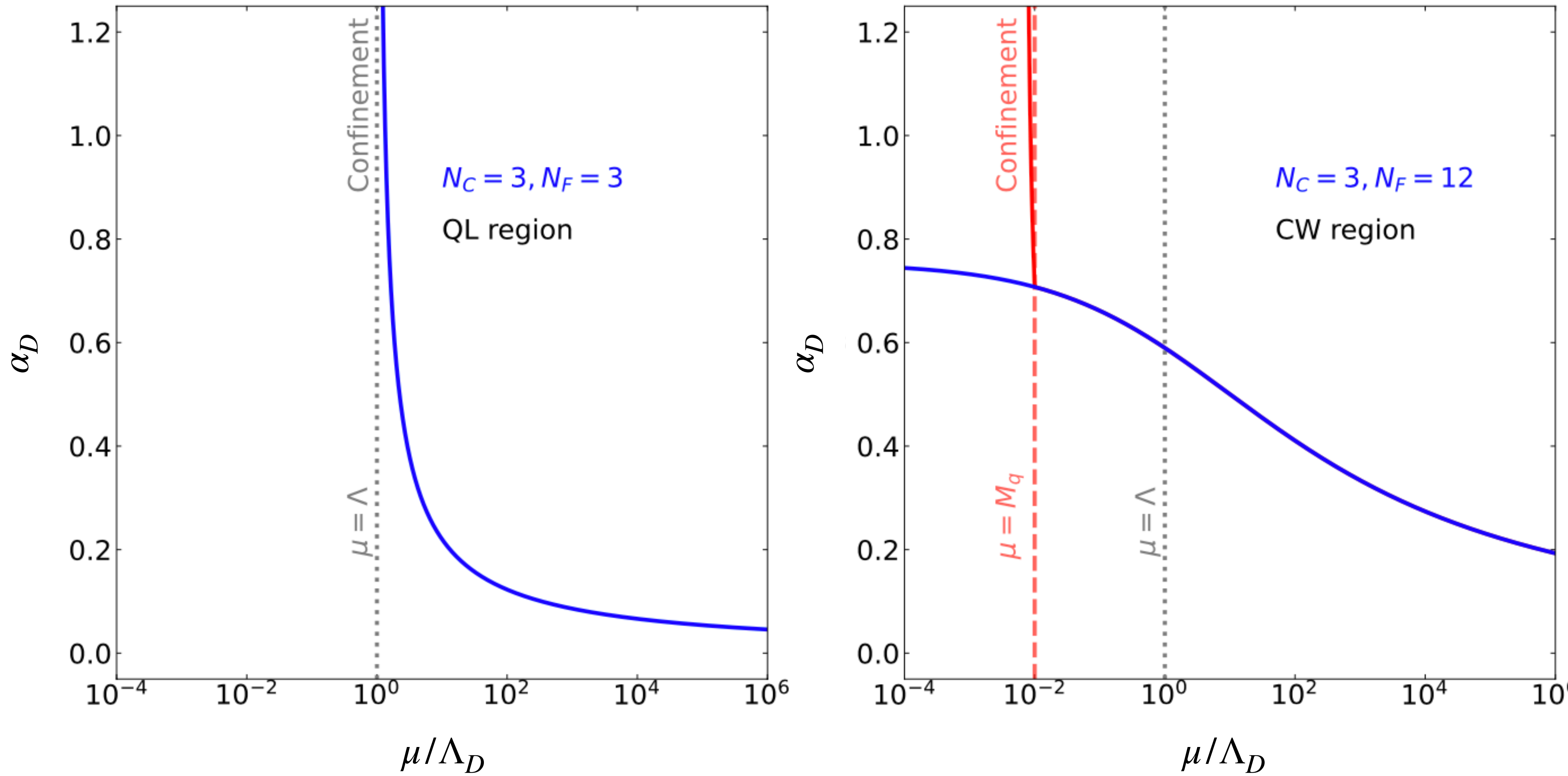
Conformal window theories

NB: This two loop picture is susceptible to large three-loop corrections!

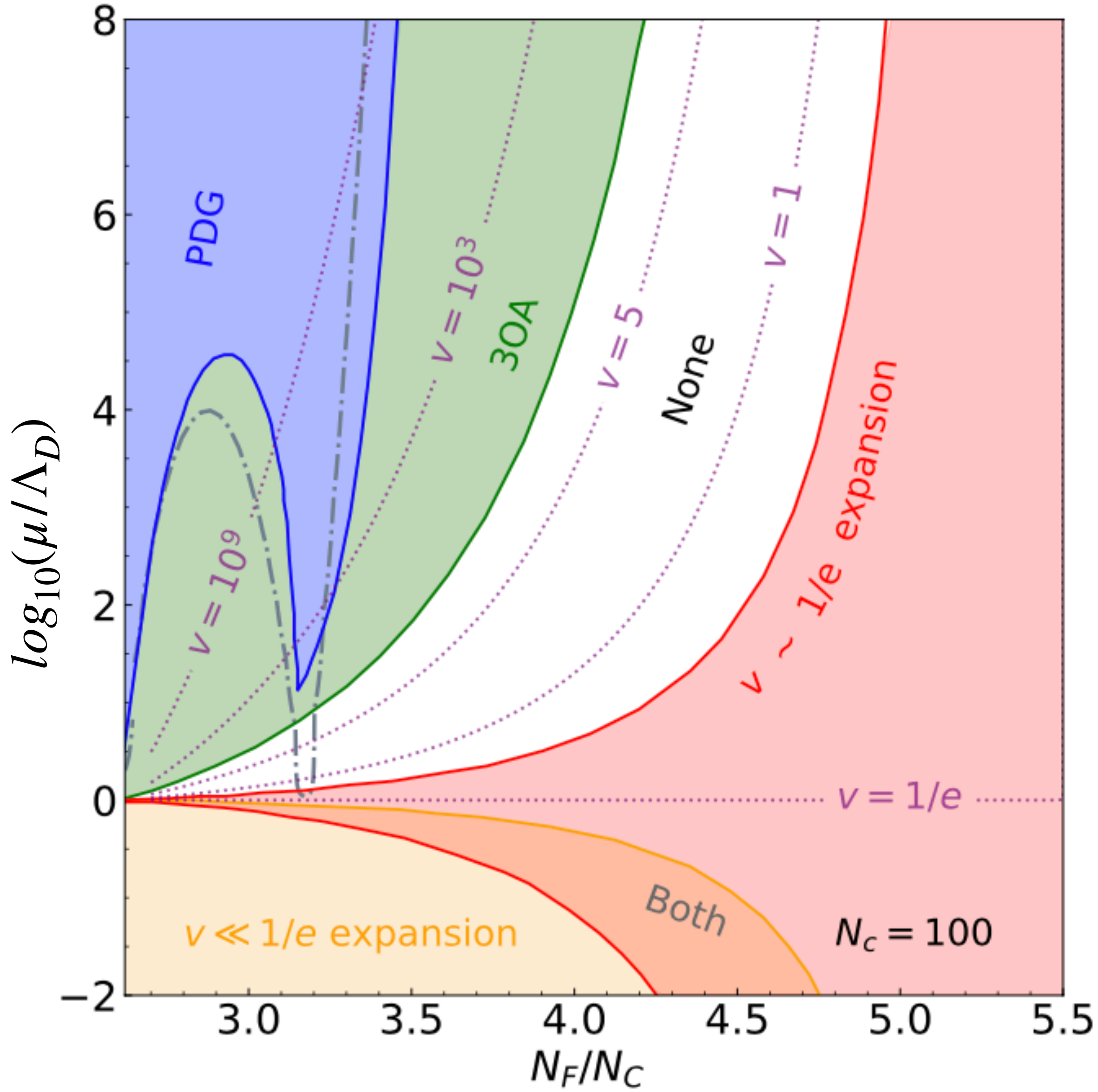


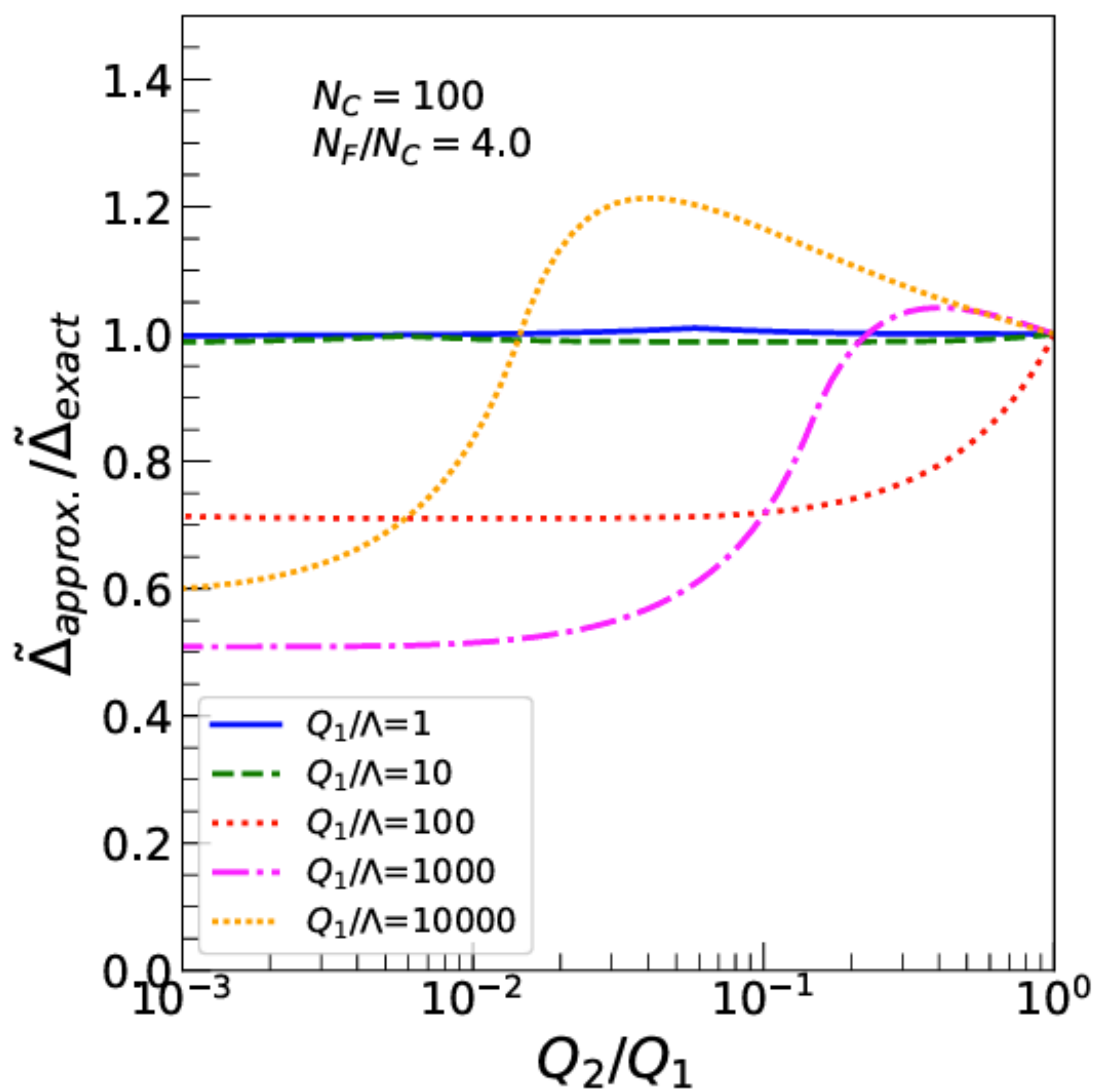
- Two loop RGE solutions for theories with $N_F/N_C \gtrsim 2.6$ contain fixed points, which change the shape of the running coupling
- Mass gap generation requires introduction of conformal symmetry breaking operators

Conformal window theories

Kulkarni, Lockyer, Strassler (arXiv:2502.18566)

There is no simple way to approximate the principle branch of Lambert W function, high energy and low energy approximations may be stitched together with interpolation procedure





Conclusions

- Dark-sector exploration remains a top priority at colliders
  - Interesting signatures are generated in presence of mass-gap
  - Reinterpreting existing searches provides a powerful strategy for devising new searches
- LHC explorations of hidden valley/darkshowers are now getting mature
  - QCD-like dark sectors: asymptotically free and are in a chirally broken regime
  - Conformal Window dark sectors: asymptotically free but do not feature chiral symmetry breaking
- QCD-like dark sectors:
  - Many obstacles still remain, including potentially substantial parton shower and hadronization uncertainties
  - We now have first theoretically consistent framework to explore QCD-like dark sectors at the LHC and make systematic progress
- Conformal window dark sectors:
  - First steps towards simulations of conformal window dark sector showers
  - Primarily rely on improving existing event generators for simulating running coupling with an Infra-Red Fixed Point