Low-energy effective description of dark Sp(4) theories

S.Kulkarni, A.Maas, S.Mee
M.Nikolic, J.Pradler, **F. Zierler**

based on [2202.05191]

universität wien
TECHNISCHE UNIVERSITÄT WIEN Vienna University of Technology
HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN
UNI GRAZ
NAWI Graz Natural Sciences
FWF Der Wissenschaftsfonds.

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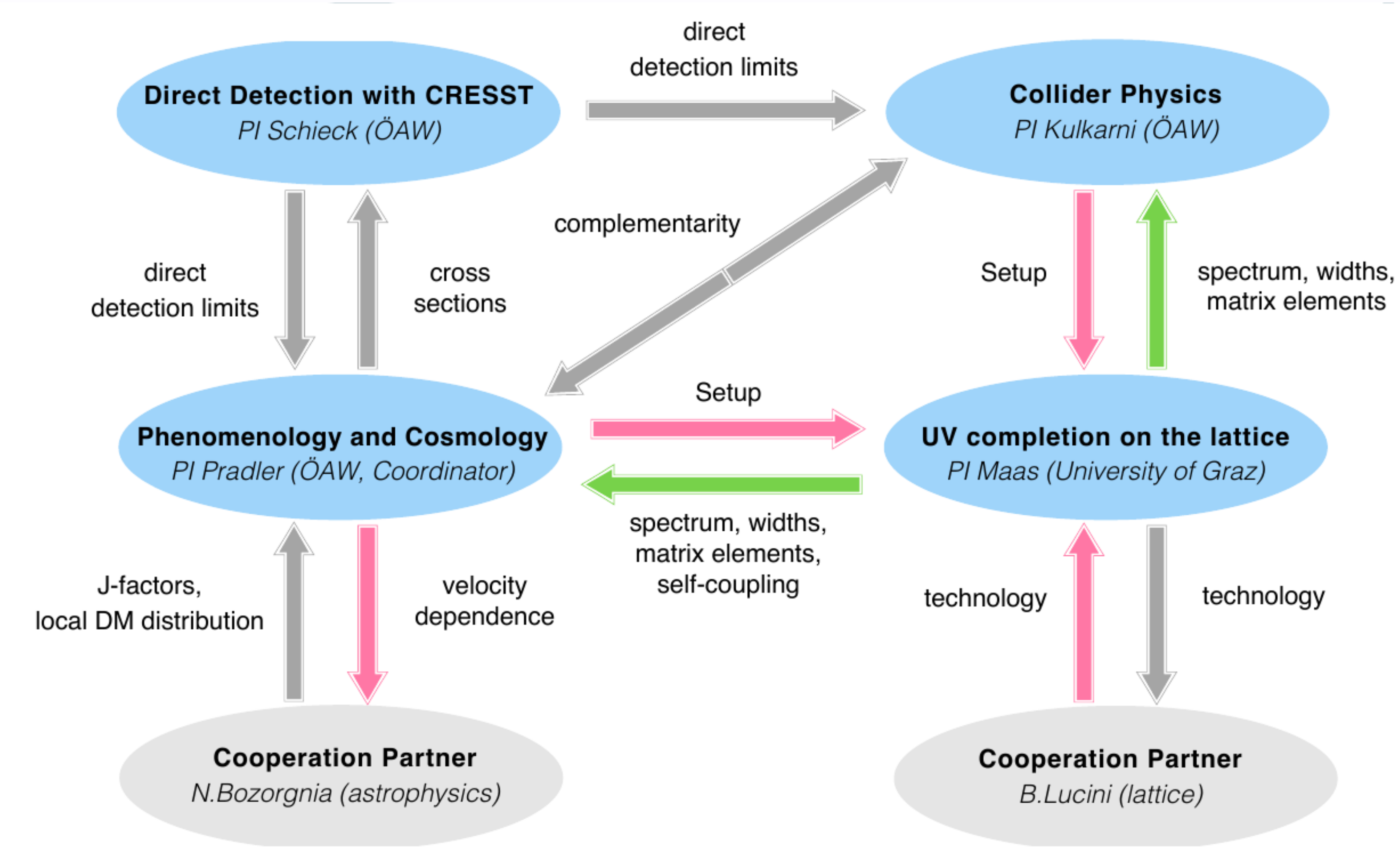
Interdisciplinary research group: Strong DM



- Combining collider and astrophysical pheno with lattice field theory and direct detection searches

Outline

1. Dark Matter (DM): Motivation
2. Strongly Interacting Massive Particles
3. Mesonic spectrum $Sp(4)$ and DM candidates
4. Effective theories and lattice constraints

Dark Matter

- Nature of Dark Matter (DM) unclear
- Only gravitational effects observed
- Hypothesis: Particle Dark Matter
  - At least one additional DM particle to SM
  - Coupling to the SM extremely weak
  - Stable over tens of billions of years

From WIMPs to SIMPs

(Strongly Interacting Massive Particles)

- WIMPs: DM as thermal relic from early universe
- Decouple below certain temperature $\rightarrow$ freeze out
- Density distribution of DM constraints theories
- Constraint given by DM depletion process

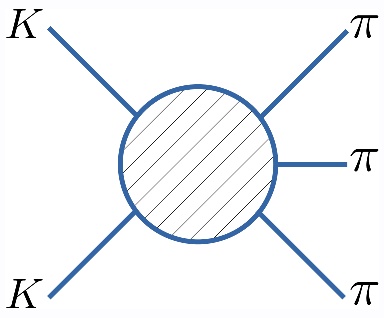
  WIMPs: $2\mathrm{DM} \rightarrow 2\mathrm{SM} \;\Rightarrow m_D \approx \mathrm{TeV}$

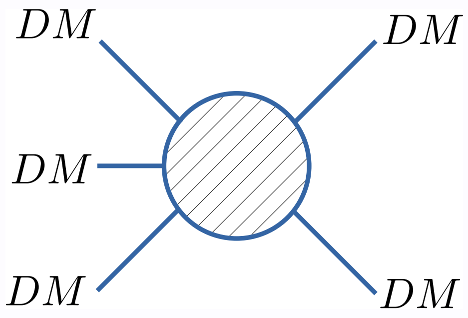
  SIMPs: $3\mathrm{DM} \rightarrow 2\mathrm{DM} \Rightarrow m_D \approx \mathcal{O}(100)\mathrm{MeV}$ **[1]**

[1] Hochberg et. al. [1402.5143] [1411.3727] [1512.07917]

$3 \to 2$ occurs in chiral effective theories!

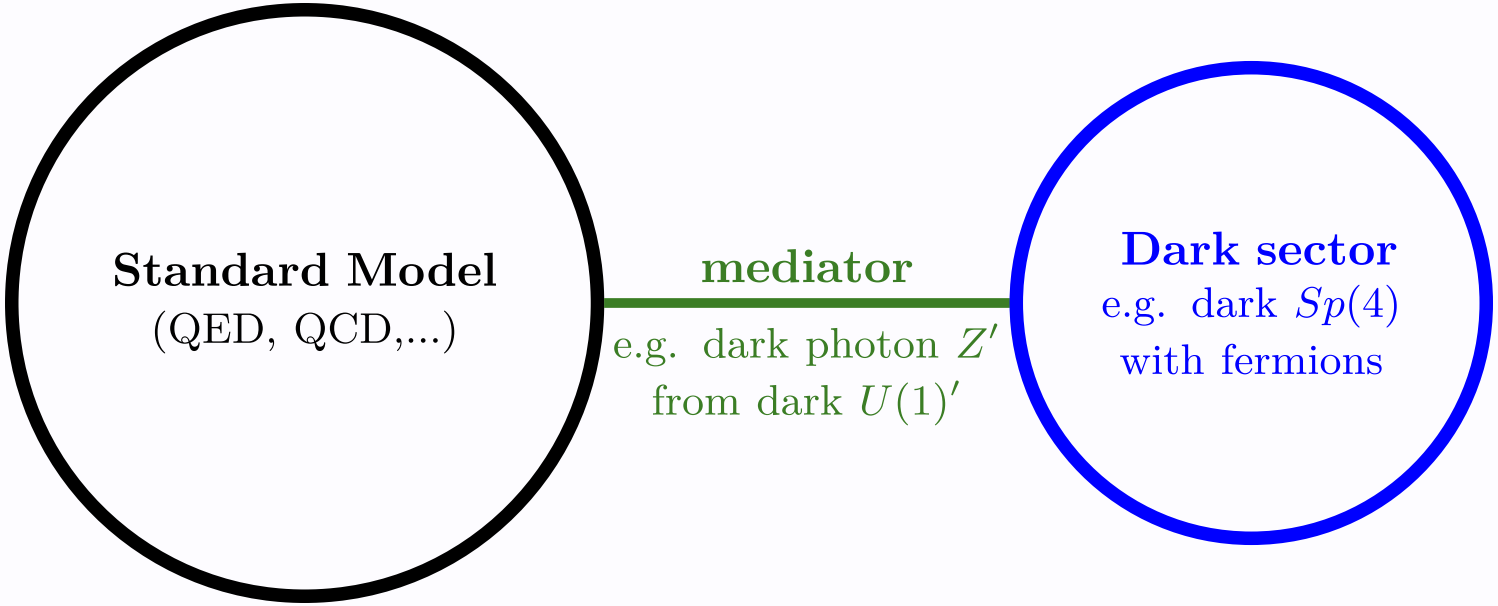
- Spontaneous chiral symmetry breaking
  $\Rightarrow$ relatively light (pseudo-)Goldstone states
  ≥ 5 pGoldstones: effective 5-point-interaction
- In QCD this describes the $2K \to 3\pi$ decay.





Idea: Non-Abelian gauge theory with $3 \to 2$
Goldstones as Dark Matter candidates + mediator

A model of SIMP Dark Matter



- Strong, confining dark sector $\Rightarrow$ dark hadrons
- **Dark fermions no not carry any SM charge**
- Small coupling to the SM via Z'-γ-mixing

We have a model. We need predictions.

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Sp(4)} + \mathcal{L}_{\text{mediator}}$$

- Dark $Sp(4)$ confines into dark hadrons
- DM canditates are bound states $\rightarrow$ non-perturbative
- Low energy effective theory (EFT) needed

- **Combine the methods with lattice field theory**
  - Derive low energy EFT for dark sector + mediator
  - Low energy constants (LECs) from lattice
  - Use EFT for astro/collider/direct detection pheno

Constructing EFTs: Symmetries

QCD with $N_f = 2$

$U(2) \times U(2)$

↓ axial anomaly | $m_u = m_d = 0$

$SU(2) \times SU(2) \times U(1)$

↓ chiral symmetry breaking *and/or* explicit breaking | $m_u = m_d = 0$, $m_u = m_d \neq 0$

$SU(2) \times U(1)$

↓ strong isospin breaking | $m_u \neq m_d$

$U(1) \times U(1)$

$\mathbf{Sp(4)_c}$ with $N_f = 2$

$U(4)$

↓ $m_u = m_d = 0$ | axial anomaly

$SU(4)$

↓ $m_u = m_d = 0$, $m_u = m_d \neq 0$ | chiral symmetry breaking *and/or* explicit breaking

$Sp(4)$

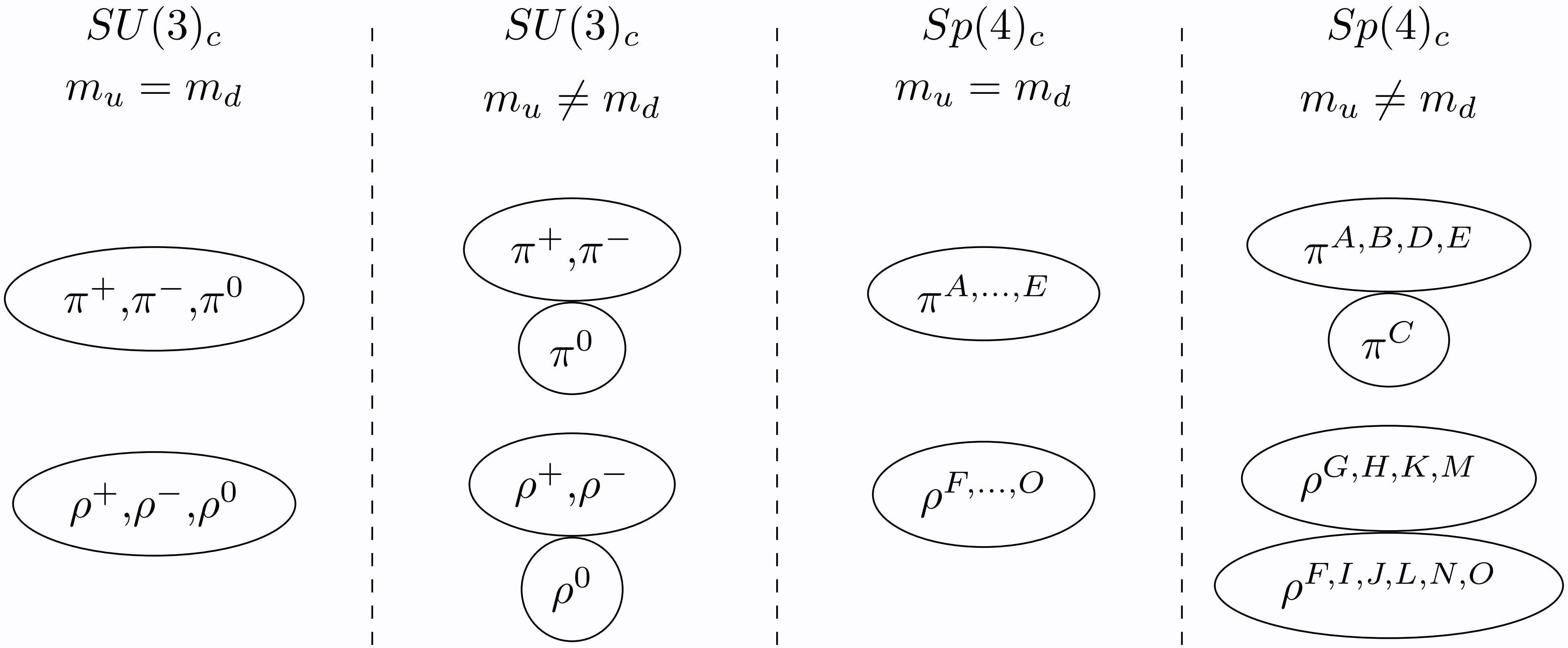
↓ $m_u \neq m_d$ | strong isospin breaking

$SU(2) \times SU(2)$

see e.g. '[hep-ph/0001171] [1205.4205] '

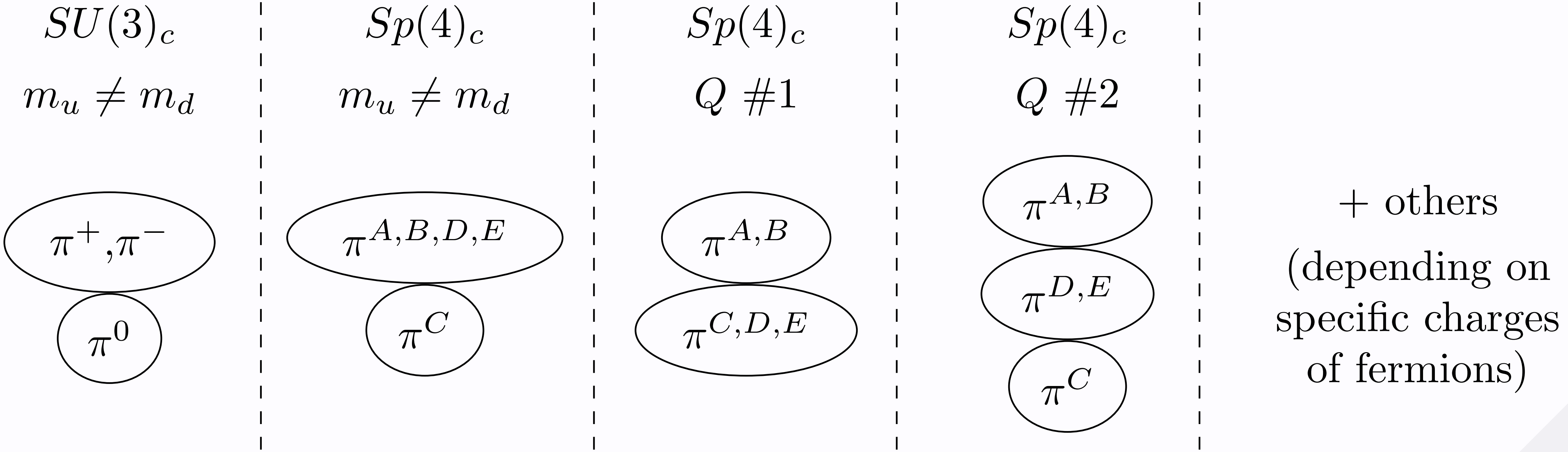
Symmetries of dark hadrons (without mediator)

- Global symmetries are enlarged compared to QCD
- New quark-quark and antiquark-antiquark states



Symmetries of dark hadrons (with Z' mediator)

- Radiative corrections break symmetries differently
- Depending on the charge assignment Q of fermions

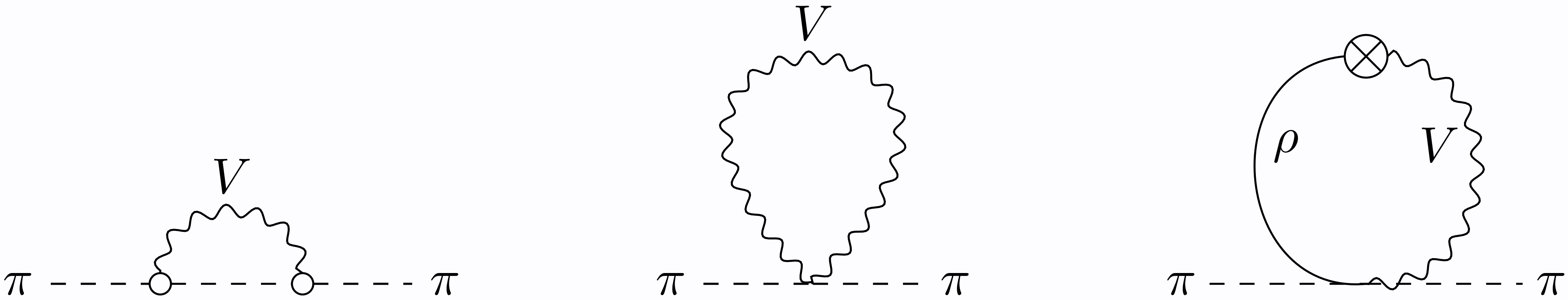


Particle stability

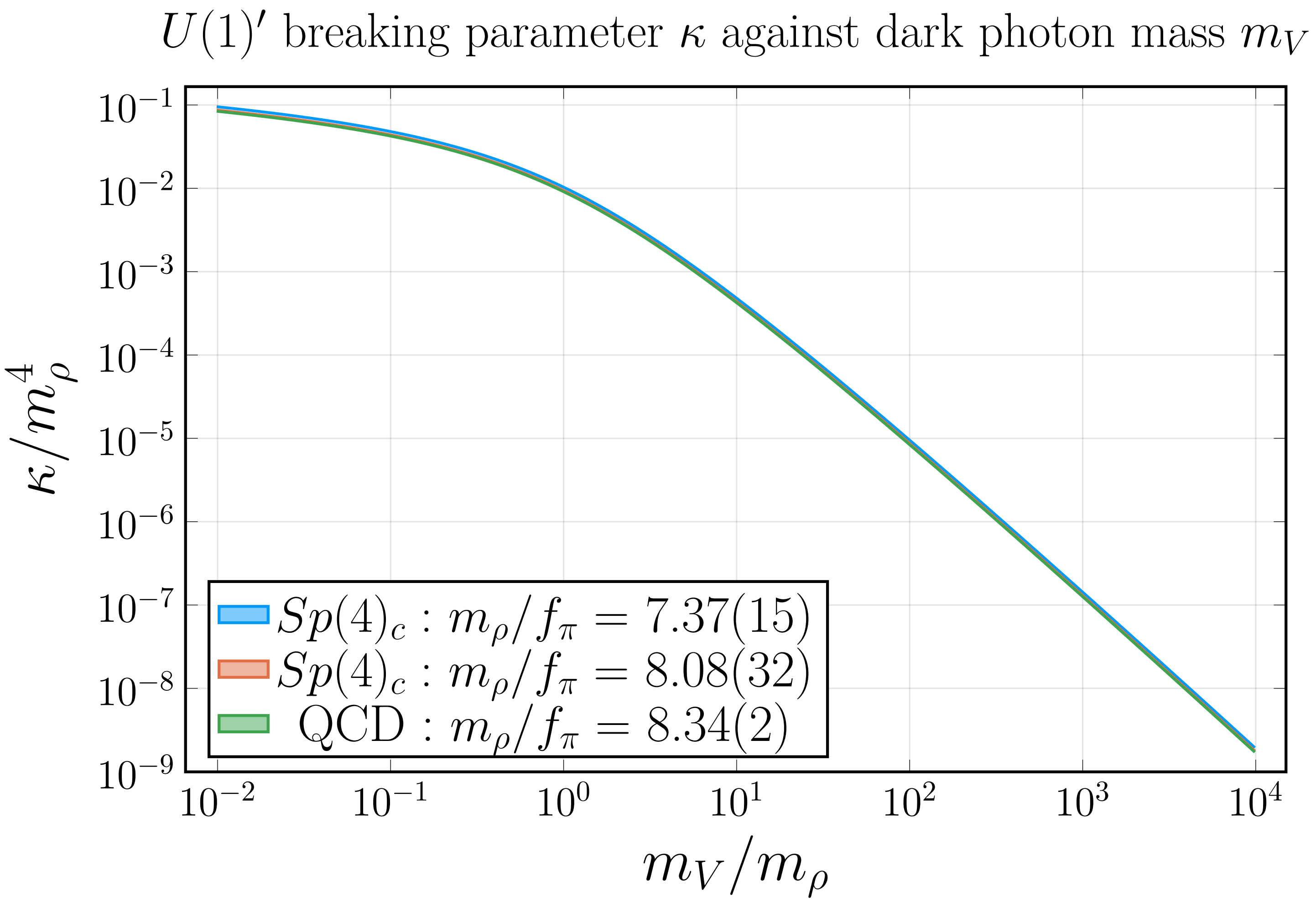
- Only multiplets are protected by symmetry
- Singlets can decay
  - $m_u = m_d$: Some charge assignments avoid singlets
  - $m_u \neq m_d$: Even without a Z' the π^C is a singlet
- For a viable DM candidate the decay of flavour singlets needs to be sufficiently supressed

Low Energy Constants from the lattice I

- Mass degenerate theory has been studied **[1]**
- Use **existing** data to constrain LEC κ in radiative pion mass splitting through vector meson ρ and dark photon V



[1] Bennett et. al. [1712.04220] [1909.12662]



- use existing lattice data **[1]**
- constrains κ vs. m_V
- similar for many gauge groups

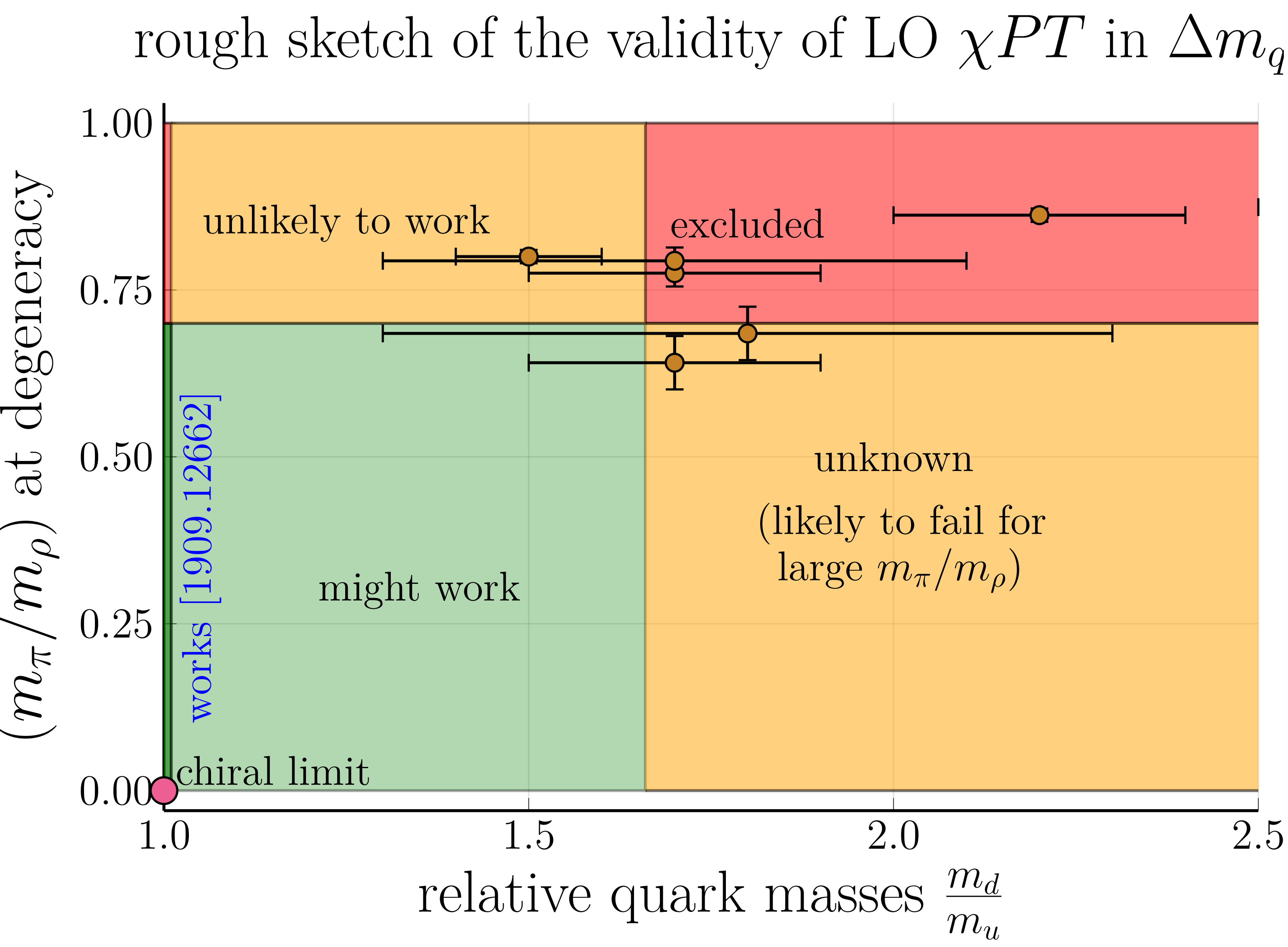
[1] Bennett et. al. [1909.12662]

Low Energy Constants from the lattice II

- **New** lattice results for isospin breaking $m_u \neq m_d$
- Relevant LECs: Pion masses and decay constants
- We have bounds on EFT validity:

$$\left(\frac{m_\pi}{m_\rho}\right)_{deg} < 0.7 \qquad \left(\frac{m_d}{m_u}\right)_{\mathrm{PCAC}} < 1.5$$

- For larger values LO χPT breaks down



- data points: breakdown of LO χPT in Δm on the lattice
- $\frac{m_d}{m_u} = 1 + \Delta m$
- $\frac{m_\pi}{m_\rho}$ fixed at degeneracy

Conclusion

- First results of the FG1 collaboration
- Systematic development of strongly interacting dark matter theories for $Sp(4)$
  - For degenerate fermions including mediator
  - For non-degenerate fermions in isolation

- Full paper: [2202.05191]

References: Global Symmetries

- [hep-ph/0001171] Kogut, Stephanov, Toublan, Verbaarschot, Zhitnitsky. Nucl. Phys. B 582, 2000
- [1205.4205] von Smekal. Nucl.Phys.B - Proceedings Supplements 228, 2012

References: SIMPs

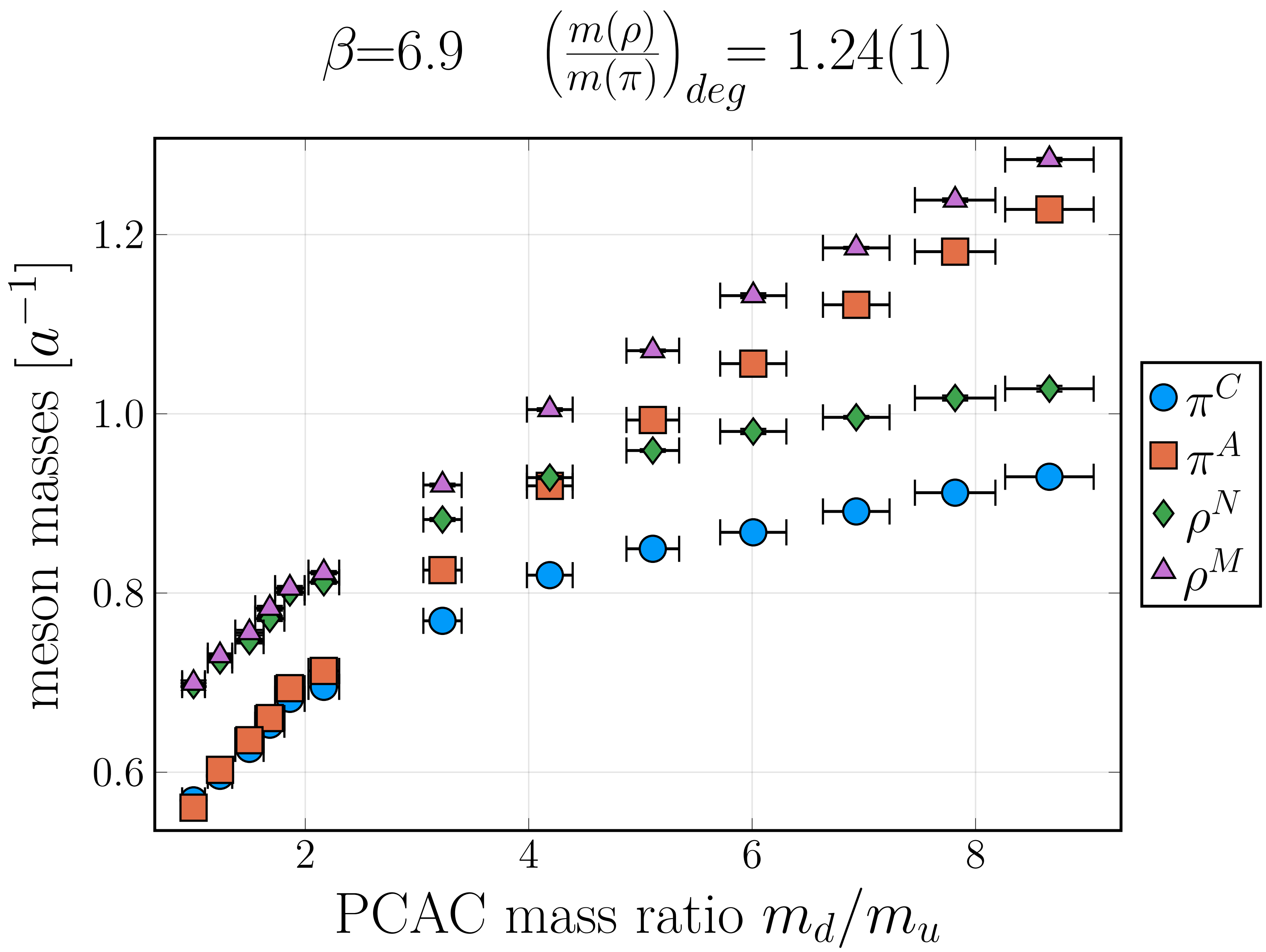
- [1402.5143] Hochberg, Kuflik, Volansky, Wacker. Phys.Rev.Lett. 113, 2014
- [1411.3727] Hochberg, Kuflik, Murayama, Volansky, Wacker. Phys.Rev.Lett. 115, 2015
- [1512.07917] Hochberg, Kuflik, Murayama. JHEP05, 2016

References: Lattice & Code

- [0805.2058]
  Del Debbio, Patella, Pica. Phys.Rev.D 81, 2010
- [1712.04220] Bennett, Hong, Lee, Lin, Lucini, Piai, Vadacchino. JHEP03, 2018
- [1909.12662] Bennett, Hong, Lee, Lin, Lucini, Piai, Rantaharju, Vadacchino. JHEP12, 2019

Backup

Dark pion and rho mesons in isolation



Flavour symmetry

- Higher symmetry than QCD-like theories
- Mixing of left- and right-handed Weyl components

$$\Psi = \begin{pmatrix} u_L \\ d_L \\ -SCu_R^* \\ -SCd_R^* \end{pmatrix} = \begin{pmatrix} u_L \\ d_L \\ \tilde{u}_R \\ \tilde{d}_R \end{pmatrix} \qquad \begin{matrix} C \ldots \text{charge conj.} \\ S \ldots \text{colour matrix} \end{matrix}$$

$$\mathcal{L}_f = i\bar{\Psi}\not{D}\Psi - \frac{1}{2}\left(\Psi^T SCM\Psi + h.c.\right)$$

- generators τ_a in fundamental repr. : $S\tau_a S = -\tau_a^T$

Extra particles?

- 3 Goldstones like the pions of QCD:
- 2 additional states: quark-quark, antiquark-antiquark
  - π_{qq} with flavour structure $u^T SC\gamma_5 d$
  - and corresponding antiquark-antiquark state

- Note the additional charge conjugation operator C
- Flavour symmetry mixes chiral components
- Consequences for **parity of diquarks!**

Alternative parity transformation

$$D : \psi(x,t) \to \pm i\gamma_0 \psi(-x,t)$$

- Still a symmetry of the system ($\mathcal{L}$ invariant)
- Commutes with flavour transforms **[1710.07218]**

  $\Rightarrow$ same D-parity in every multiplet
  - all *Goldstones* are *pseudoscalar*
  - all members of ρ-multiplet are *vectors*