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Beyond $3 \to 2$:
Towards Realistic SIMP Dark Matter

Halvor Melkild
halvor.melkild@fys.uio.no

In collaboration with T. Bringmann, H. Kolesova, D. Krichevskiy, J. Pomper

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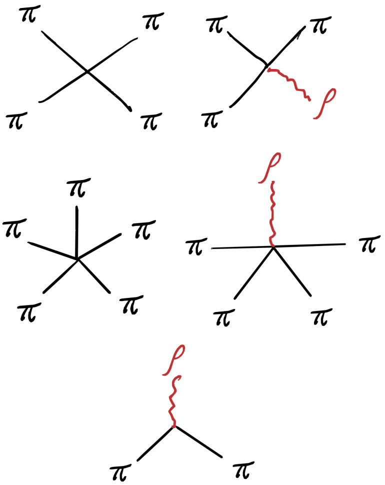
Outline

- What are SIMPs?
- How do SIMPs freeze out?
- SIMPs with vector mesons



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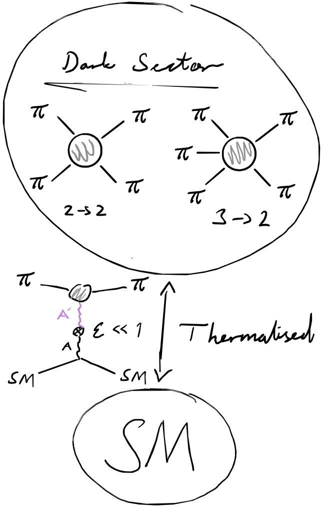
Strongly Interacting Massive Particles (SIMP)

1. UV-theory with QCD-like gauge interaction
   - E.g., $SU(N)$, $Sp(N)$, $SO(N)$
2. Confinement breaks flavour symmetry
   - Dark pions are pseudo-Nambu-Goldstone bosons
3. Effective ChPT for dark pions
   - Dark Matter candidate if stable
4. Thermal equil. with SM through $U(1)_{\mathrm{D}}$ portal

$$\mathcal{L} \supset -\epsilon A'_{\mu\nu} F^{\mu\nu}$$



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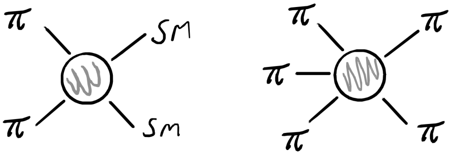
Thermal Freeze-Out

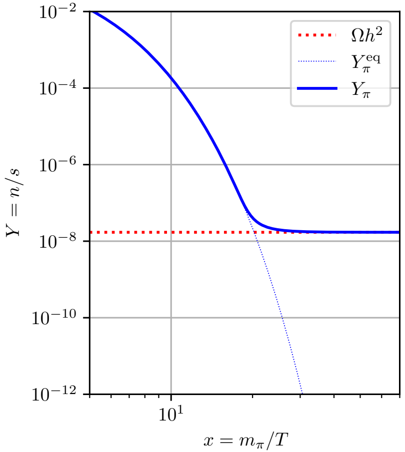


WIMP: DM in equilibrium with thermal bath.

SIMP: Number changing process in Dark Sector

Boltzmann equation:

$$\frac{dn}{dt} + 3Hn = \begin{cases} -\langle \sigma v \rangle (n^2 - n_{\text{eq}}^2), & \text{WIMP} \\ -\langle \sigma v^2 \rangle (n^3 - n_{\text{eq}} n^2), & \text{SIMP} \end{cases}$$



Phenomenology of SIMPs

Initial idea:

- $3\pi \to 2\pi$ process fixes the relic abundance of Dark Matter

Consequences:

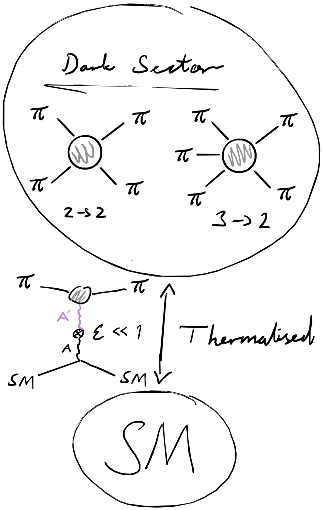
- Sub-GeV Dark Matter

$$m_\pi \sim \alpha_{\text{eff}}(T_{\text{eq}}^2 M_{\text{Pl}})^{1/3} \sim 100 \text{ MeV}$$

- Coupling to the Standard Model needed
  - Must thermalise with SM
  - ϵ could be small $\to$ Not connected to freeze-out
- Sizeable self-interactions

$$\sigma_{\text{scatter}} \propto \left(\frac{m_\pi}{f_\pi}\right)^4 \frac{1}{m_\pi^2}$$

Hochberg et al. [1402.5143, 1411.3727]



Beyond purely pionic SIMP DM

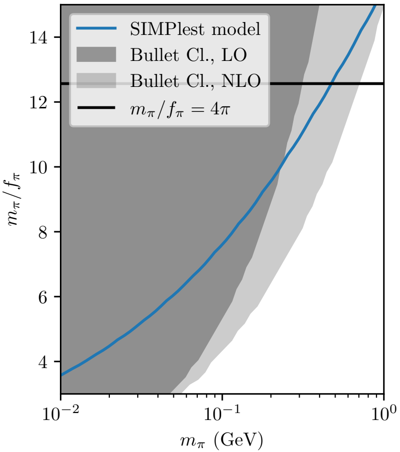
Problem:
Pionic SIMP DM is ruled out for small values of m_π/f_π by Bullet cluster constraint:

$$\frac{\sigma_{\text{scatter}}}{m_\pi} \lesssim 1\ \text{cm}^2/\text{g} \tag{1}$$

Hochberg et al. [1411.3727], Hansen et al. [1507.01590]

Solution
Include vector mesons in the model building:

Choi et al. [1801.07726], Berlin et al. [1801.05805], Bernreuther et al. [2311.17157]



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Kolesova, Krichevskiy, Kulkarni [2509.07102]

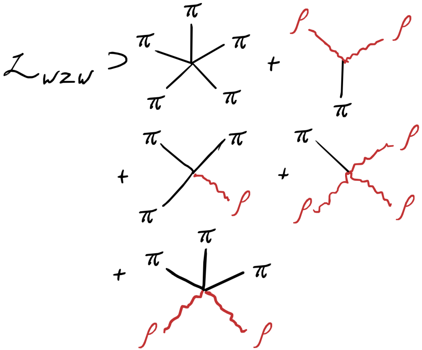
Hidden Local Symmetry

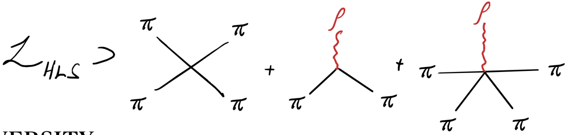
- Vector mesons are gauge bosons of a HLS corresponding to the unbroken flavour symmetry.

  Bando, Kugo, Yamawaki (Phys. Rep. 164, 1988)

- Lattice results relate m_ρ and f_π

- Assuming Vector Meson Dominance for Dark Photon portal





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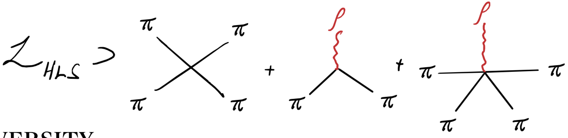

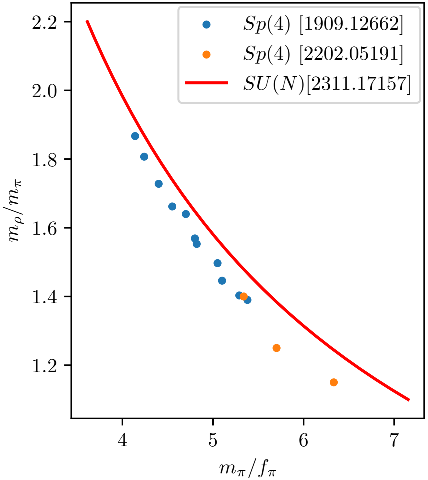

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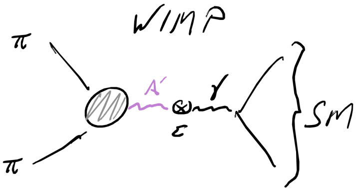
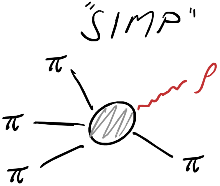
Boltzmann equations

$$
\begin{aligned}
\frac{\mathrm{d}n_\pi}{\mathrm{d}t} &+ 3Hn_\pi \\
&= -\langle\sigma v(\pi\pi \to \mathrm{SM})\rangle_{\mathrm{eff}}\left(n_\pi^2 - (n_\pi^{\mathrm{eq}})^2\right) \\
&\quad + \langle\sigma v(\pi\rho \to \pi\pi)\rangle_{\mathrm{eff}}\left(n_\pi n_\rho - n_\pi^2 \frac{n_\rho^{\mathrm{eq}}}{n_\pi^{\mathrm{eq}}}\right) \\
&\quad - \langle\sigma v^2(3\pi \to 2\pi)\rangle_{\mathrm{eff}}\left(n_\pi^3 - n_\pi^2 n_\pi^{\mathrm{eq}}\right) \\
&\quad - 2\langle\sigma v^2(3\pi \to \pi\rho)\rangle_{\mathrm{eff}}\left(n_\pi^3 - n_\pi n_\rho \frac{(n_\pi^{\mathrm{eq}})^2}{n_\rho^{\mathrm{eq}}}\right) \\
&\quad - 3\langle\sigma v^2(3\pi \to 2\rho)\rangle_{\mathrm{eff}}\left(n_\pi^3 - (n_\pi^{\mathrm{eq}})^3 \left(\frac{n_\rho}{n_\rho^{\mathrm{eq}}}\right)^2\right)
\end{aligned}
$$

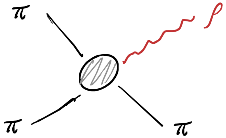
$$
\begin{aligned}
\frac{\mathrm{d}n_\rho}{\mathrm{d}t} &+ 3Hn_\rho \\
&= -\langle\Gamma(\rho \to \mathrm{SM})\rangle_{\mathrm{eff}}\left(n_\rho - n_\rho^{\mathrm{eq}}\right) \\
&\quad - \langle\sigma v(\pi\rho \to \pi\pi)\rangle_{\mathrm{eff}}\left(n_\pi n_\rho - n_\pi^2 \frac{n_\rho^{\mathrm{eq}}}{n_\pi^{\mathrm{eq}}}\right) \\
&\quad + \langle\sigma v^2(3\pi \to \pi\rho)\rangle_{\mathrm{eff}}\left(n_\pi^3 - n_\pi n_\rho \frac{(n_\pi^{\mathrm{eq}})^2}{n_\rho^{\mathrm{eq}}}\right) \\
&\quad + 2\langle\sigma v^2(3\pi \to 2\rho)\rangle_{\mathrm{eff}}\left(n_\pi^3 - (n_\pi^{\mathrm{eq}})^3 \left(\frac{n_\rho}{n_\rho^{\mathrm{eq}}}\right)^2\right)
\end{aligned}
$$

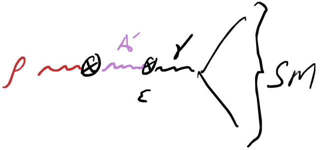
Freeze-out scenarios with vector mesons





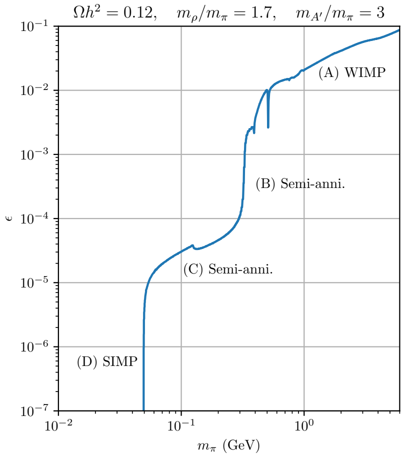
Semi-annihilation





Freeze-out scenarios with $Sp(4)$

- WIMP
  - (A) $2\pi \leftrightarrow$ SM
- Semi-annihilation
  - (B) $2\pi \leftrightarrow \pi\rho$: Vector mesons are in equilibrium with SM at freeze-out.
  - (C) $\rho \leftrightarrow$ SM: Pions and Vector mesons are in equilibrium at freeze-out.
- SIMP with vector meson
  - (D) $3\pi \leftrightarrow \pi\rho$



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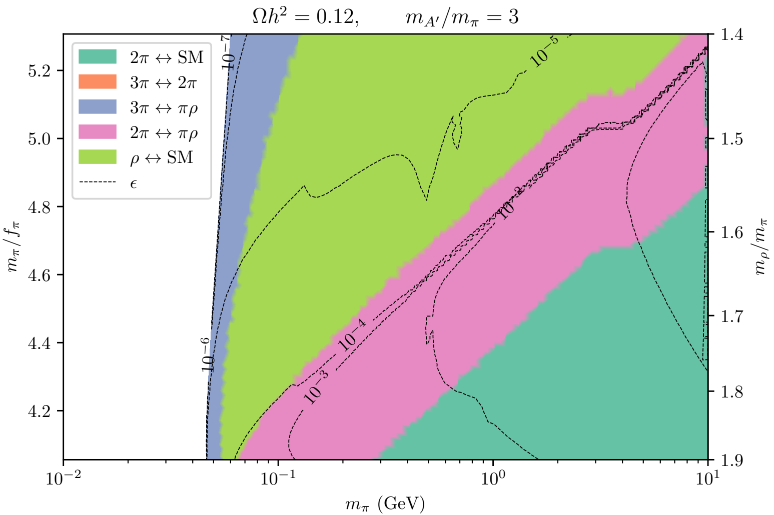
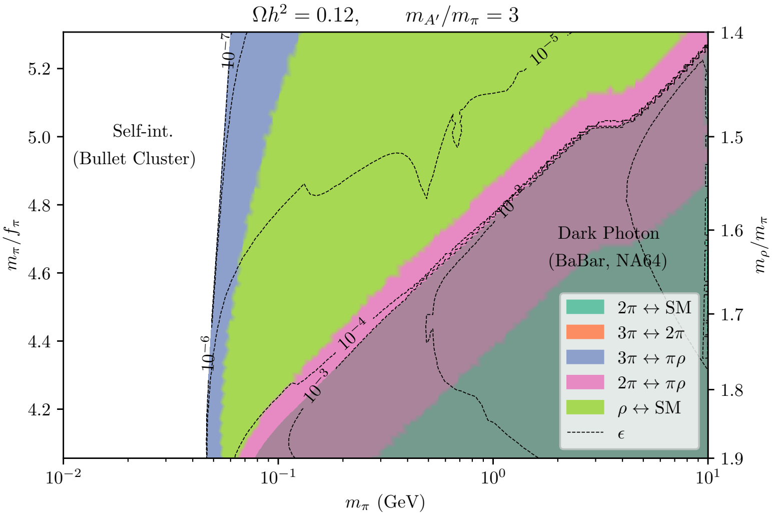
Interactions responsible for freeze-out



Constraints on freeze-out scenarios



Constraints

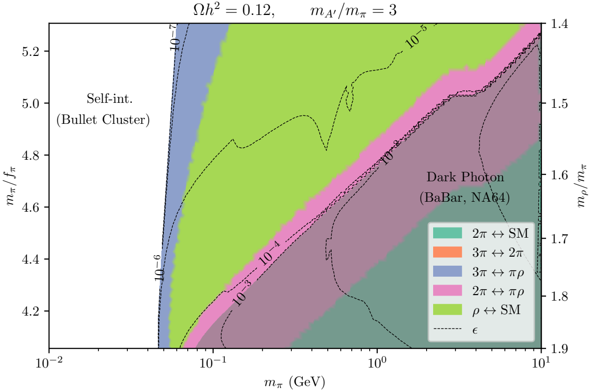
- Bullet cluster constraint on self-interaction:

$$\frac{\sigma_{\text{scatter}}}{m_\pi} \lesssim 1\,\text{cm}^2/\text{g}$$

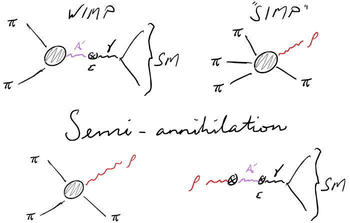
- Dark photon constraints set upper limit on ϵ
  - BaBar, Belle II, NA64

Berlin et al. [1801.05805]

- The same experiments can search for decaying vector mesons

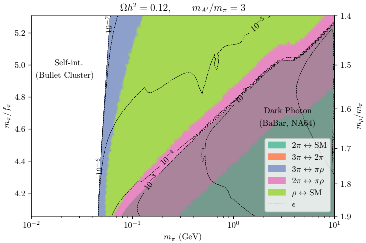


Summary



1. Vector mesons **must** be included in SIMP studies
2. HLS + Lattice results $\Rightarrow$
   - **Consistent** and **predictive** model
3. Rich phenomenology in Cosmology and at Colliders

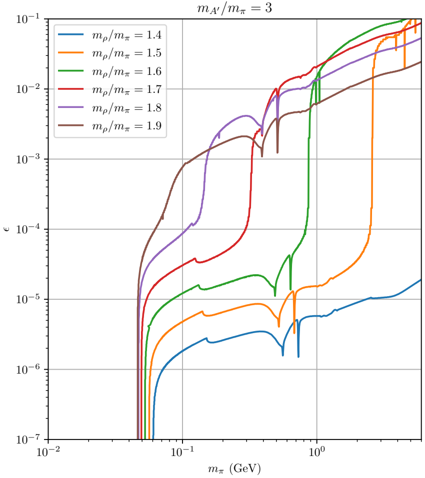
Work in progress!

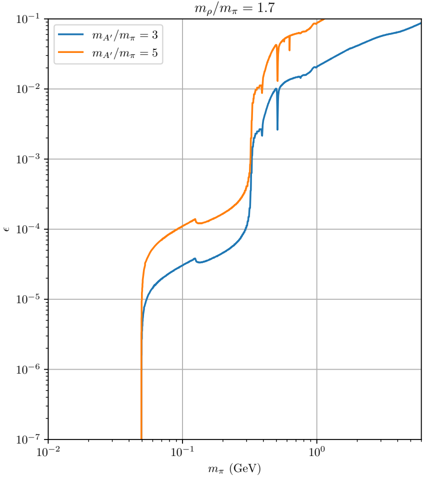


Thank you for the attention!

Backup

Varying parameters





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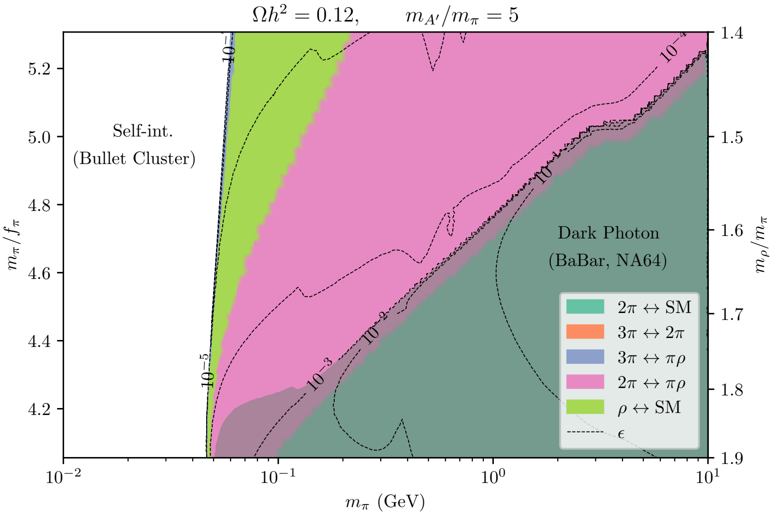
Freeze-out scenarios with vector mesons



HLS Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\mathrm{HLS}}^{\mathrm{IR};(2)} &= -2\beta\left(m_u+m_d\right)+\frac{1}{2}\partial_\mu\pi^a\partial_\mu\pi^a-\frac{2\beta}{f_\pi^2}\pi^a\pi^b\left\langle\bar{X}T^aT^b\right\rangle \\
&+\frac{3\alpha_0-4}{6f_\pi^2}\pi^a\pi^b\partial_\mu\pi^c\partial^\mu\pi^d\left\langle T^a\left[T^b,T^c\right]T^d\right\rangle+\frac{2\beta}{3f_\pi^4}\pi^a\pi^b\pi^c\pi^d\left\langle\bar{X}T^aT^bT^cT^d\right\rangle \\
&+\frac{\alpha_0 f_\pi^2 g_V^2}{2}V_\mu^\alpha V^{\mu,\alpha}+\frac{\alpha_0 f_\pi^2 e_D^2 q^2}{2}Z_\mu Z^\mu-qe_Dg_V\alpha_0 f_\pi^2 Z^\mu V_\mu^1 \\
&-\frac{g_V\alpha_0}{2}f^{\alpha bc}V_\mu^\alpha\partial^\mu\pi^b\pi^c+e_D\left(\frac{\alpha_0}{2}-1\right)qf^{\hat{1}bc}Z_\mu\partial^\mu\pi^b\pi^c \\
&+\frac{1-\alpha_0}{2\sqrt{2}}e_D^2q^2f^{\hat{1}bc}Z_\mu Z^\mu\pi^a\pi^b\left(\delta_{a,5}\delta_{c,4}-\delta_{c,5}\delta_{a,4}\right) \\
&+iqe_Dg_V\alpha_0\pi^a\pi^bV_\mu^\alpha Z^\mu\left(-f^{\hat{1}bc}\left\langle X^\alpha T^aT^c\right\rangle+f^{\hat{1}ac}\left\langle X^\alpha T^cT^b\right\rangle\right) \\
&+\left(2-\frac{7}{4}\alpha_0\right)\frac{ie_Dq}{3f_\pi^2}Z^\mu\pi^a\pi^b\pi^c\partial_\mu\pi^d\left\langle\left(3T^a\left[T^d,T^c\right]T^b+\left[T^aT^bT^c,T^d\right]\right)X^1\right\rangle \\
&+\frac{ig_V\alpha_0}{12f_\pi^2}V_\mu^\alpha\pi^a\pi^b\pi^c\partial^\mu\pi^d\left\langle\left(3T^a\left[T^d,T^c\right]T^b+\left[T^cT^aT^b,T^d\right]\right)X^\alpha\right\rangle+\mathcal{O}(6\text{ fields}),
\end{aligned}
$$

NLO Lagrangian

$$
\begin{aligned}
\mathcal{L}^{\mathrm{NLO}} = \frac{id_{\mathcal{R}}}{8\pi^2}\varepsilon^{\mu\nu\gamma\delta}\Bigg[& ie_D\frac{\alpha_1}{f_\pi^3}r_7^{abc}Z_\mu\partial_\nu\pi^a\partial_\gamma\pi^b\partial_\delta\pi^c + ig_V\frac{\alpha_1}{f_\pi^3}r_6^{\alpha abc}V_\mu^\alpha\partial_\nu\pi^a\partial_\gamma\pi^b\partial_\delta\pi^c \\
& - ie_Dg_V^2\frac{1}{f_\pi}\left(\alpha_2 r_9^{\alpha\beta a} + \alpha_3 r_{22}^{\alpha\beta a}\right)V_\mu^\alpha V_\nu^\beta Z_\gamma\partial_\delta\pi^a - ig_V^3\frac{1}{f_\pi}\left(\alpha_2 r_{10}^{\alpha\beta\omega a} + \alpha_3 r_{23}^{\alpha\beta\omega a}\right)V_\mu^\alpha V_\nu^\beta V_\gamma^\omega\partial_\delta\pi^a \\
& + e_Dg_V\frac{\alpha_3 r_{14}^{\alpha a}}{2f_\pi}\bar{V}_{\mu\nu}^{\ \alpha}Z_\gamma\partial_\delta\pi^a + g_V^2\frac{\alpha_3 r_{15}^{\alpha\beta a}}{2f_\pi}\bar{V}_{\mu\nu}^{\ \alpha}V_\gamma^\beta\partial_\delta\pi^a + e_Dg_V\frac{\alpha_4 r_{26}^{\alpha a}}{2f_\pi}V_\mu^\alpha Z_{\nu\gamma}\partial_\delta\pi^a \\
& - \frac{1}{f_\pi^5}\left(-\frac{8}{15}r_1^{abcde} + \frac{\alpha_1}{2}r_5^{abcde}\right)\pi^a\partial_\mu\pi^b\partial_\nu\pi^c\partial_\gamma\pi^d\partial_\delta\pi^e + ie_D\frac{1}{f_\pi^3}\left(-\frac{2}{9}r_4^{abc} + \frac{\alpha_4}{4}r_{30}^{abc}\right)Z_{\mu\nu}\pi^a\partial_\gamma\pi^b\partial_\delta\pi^c \\
& + e_Dg_V\frac{1}{f_\pi^3}\left(\alpha_1 r_8^{\alpha abc} + \frac{\alpha_2}{2}r_{13}^{\alpha abc}\right)V_\mu^\alpha Z_\nu\pi^a\partial_\gamma\pi^b\partial_\delta\pi^c + g_V^2\frac{1}{f_\pi^3}\left(\frac{\alpha_2}{2}r_{12}^{\alpha\beta abc} + \frac{\alpha_3}{2}r_{25}^{\alpha\beta abc}\right)V_\mu^\alpha V_\nu^\beta\pi^a\partial_\gamma\pi^b\partial_\delta\pi^c \\
& - e_Dg_V^3\frac{1}{f_\pi}\left(\alpha_2 r_{11}^{\alpha\beta\omega a} + \alpha_3 r_{24}^{\alpha\beta\omega a}\right)V_\mu^\alpha V_\nu^\beta V_\gamma^\omega A_\delta\pi^a + ig_V\frac{\alpha_3}{4f_\pi^3}r_{19}^{\alpha abc}\bar{V}_{\mu\nu}^{\ \alpha}\pi^a\partial_\gamma\pi^b\partial_\delta\pi^c \\
& - ie_Dg_V^2\frac{\alpha_3}{2f_\pi}r_{16}^{\alpha\beta a}\bar{V}_{\mu\nu}^{\ \alpha}V_\gamma^\beta A_\delta\pi^a - ie_D^2g_V\frac{\alpha_4}{2f_\pi}r_{27}^{\alpha a}V_\mu^\alpha F_{\nu\gamma}A_\delta\pi^a \\
& + e_D^2\frac{1}{f_\pi^3}\left(\frac{\alpha_4}{4}r_{31}^{abc} + \frac{\alpha_4}{4}r_{33}^{abc} - \frac{2}{9}r_3^{abc} + \frac{\alpha_4}{4}r_{29}^{abc}\right)F_{\mu\nu}A_\gamma\pi^a\pi^b\partial_\delta\pi^c \\
& + e_Dg_V\frac{1}{f_\pi^3}\left(\frac{\alpha_3}{12}r_{17}^{\alpha abc} + \frac{\alpha_3}{4}r_{20}^{\alpha abc} + \frac{\alpha_3}{4}r_{21}^{\alpha abc}\right)\bar{V}_{\mu\nu}^{\alpha}A_\gamma\pi^a\pi^b\partial_\delta\pi^c \\
& + g_V^2\frac{\alpha_3}{12f_\pi^3}r_{18}^{\alpha\beta abc}\bar{V}_{\mu\nu}^{\ \alpha}V_\gamma^\beta\pi^a\pi^b\partial_\delta\pi^c + e_Dg_V\frac{1}{f_\pi^3}\left(\frac{\alpha_4}{12}r_{28}^{\alpha abc} + \frac{\alpha_4}{4}r_{32}^{\alpha abc}\right)V_\mu^\alpha F_{\nu\gamma}\pi^a\pi^b\partial_\delta\pi^c \\
& - e_D^2\frac{r_2^{abc}}{36f_\pi^3}F_{\mu\nu}F_{\gamma\delta}\pi^a\pi^b\pi^c\Bigg] + \mathcal{O}(6\text{ fields})
\end{aligned}
$$

SIMP models

Representation of the fermions	Complex	Pseudoreal	Real
Example: Fundamental rep.	$SU(N_c)$	$Sp(N_c)$	$O(N_c)$
Chiral symmetry breaking pattern	$SU(N_F) \times SU(N_F)/SU(N_F)$	$SU(2N_F)/Sp(2N_F)$	$SU(2N_F)/SO(2N_F)$
Number of pions	$N_F^2 - 1$	$(2N_F + 1)(N_F - 1)$	$N_F(2N_F + 1) - 1$

Halvor Melkild
E-mail: halvor.melkild@fys.uio.no
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