Classification of dark pion multiplets as dark matter candidates and displaced decays

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Context I

- We know there is dark matter and the WIMP paradigm is under tension (direct detection, indirect detection...).
  - Looking for new ideas
- One interesting possibility is that dark matter consists of the pseudo-Goldstone mesons of a new confining sector.
  - Dark pions

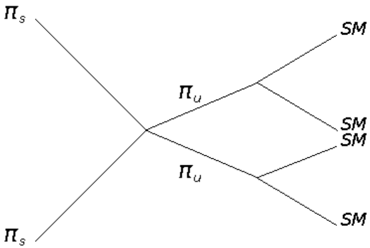
Context II

Why should we study dark pions?

- They are theoretically well motivated.
  - Neutral naturalness (Twin Higgs) (hep-ph/0607160)
  - Explanation of certain excesses (1601.07556)
  - Exoteric (hep-ph/0607160)
- They naturally accommodate more exotic and less constrained dark matter production mechanisms.
  - SIMP (1402.5143)
  - ELDER DM (1512.04545)
  - Codecaying DM (1607.03110)
- They lead to dark jets.
  - Theoretical work (1502.05409, 1503.00009, 1612.00850)
  - Experimental work (1810.10069)

Context III

- An interesting possibility is that some of the dark pions are stable and some are unstable.
- Then, the stable dark pions can act as dark matter and their interactions with the unstable ones control the dark matter abundance.
- Interactions with the SM are not required to be very strong.



Goals

- Classify multiplets of dark pions in terms of their symmetry breaking structure
- Analyze their resulting viability as dark matter candidates
- Map this to the corresponding collider phenomenology

Definition of the problem I

- Assume a new confining group $\mathcal{G}$.
- Assume a set of Dirac dark quarks q_i of mass m_i charged under $\mathcal{G}$ but neutral under the SM gauge groups.
- Assume an approximate flavor symmetry between the q_i characterized by the group G.

Definition of the problem II

- Assuming the dark quarks are not too heavy, G will be broken spontaneously by the condensate to the subgroup H:

$$G \to H.$$

- This results in a set of pseudo-Goldstone mesons, the dark pions, which form a representation of H.

Definition of the problem III

- Assume that explicit symmetry breaking breaks H to h:

$$H \to h.$$

- This decomposes the pions, which formed a single representation of H, into several representations of h.
- The group h will be in general sufficient to maintain some pions stable, but not all of them.

Definition of the problem IV

- Summary:

$$G \xrightarrow{\text{CSB}} H \xrightarrow{\text{EB}} h.$$

- The Standard Model as an example:

$$SU(3)_L \times SU(3)_R \to SU(3)_V \to U(1)_{EM}.$$

Category I: Example I

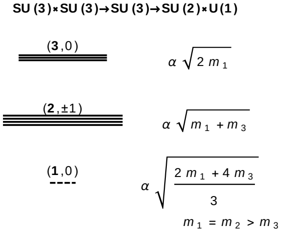
Consider the following example:

- Three dark quarks charged under a complex representation of the confining group $\mathcal{G}$.
- The two first dark quarks, q_1 and q_2, have an $SU(2)$ symmetry between them.
- The third quark q_3 has either a different mass or interactions than q_1 and q_2.
- Assume $m_1 > m_3$.

Then, the pattern of symmetry breaking is:

$$SU(3) \times SU(3) \to SU(3) \to SU(2) \times U(1).$$

Category I: Example II



- $(\mathbf{3}, 0)$
  - Stable
  - Annihilation to unstable pions kinematically allowed: $(\mathbf{3}, 0)(\mathbf{3}, 0) \to (\mathbf{1}, 0)(\mathbf{1}, 0)$
- $(\mathbf{2}, \pm 1)$
  - Stable
  - Annihilation to unstable pions kinematically allowed: $(\mathbf{2}, +1)(\mathbf{2}, -1) \to (\mathbf{1}, 0)(\mathbf{1}, 0)$
- $(\mathbf{1}, 0)$
  - Unstable

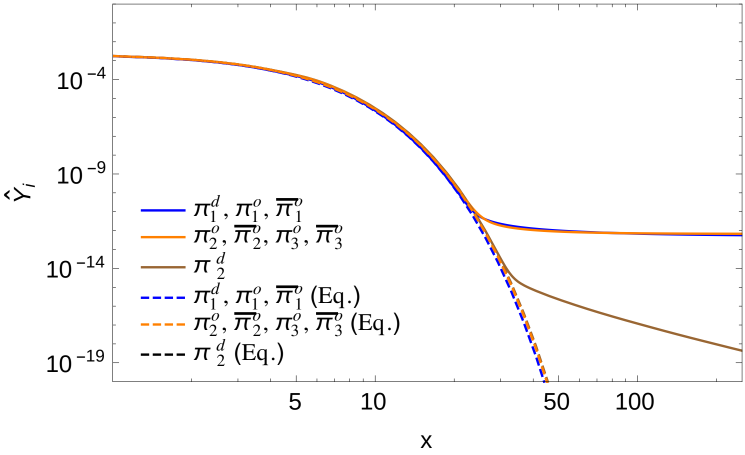
Category I: Cosmological constraints

Constraints:

- Indirect detection
  - If stable pions can annihilate to unstable ones via a kinematically allowed process, they will produce an indirect detection signal.
  - Plank, Fermi-LAT, AMS-02.
- Unitarity
- Require to reproduce the correct dark matter abundance (used to set the pion decay constant)

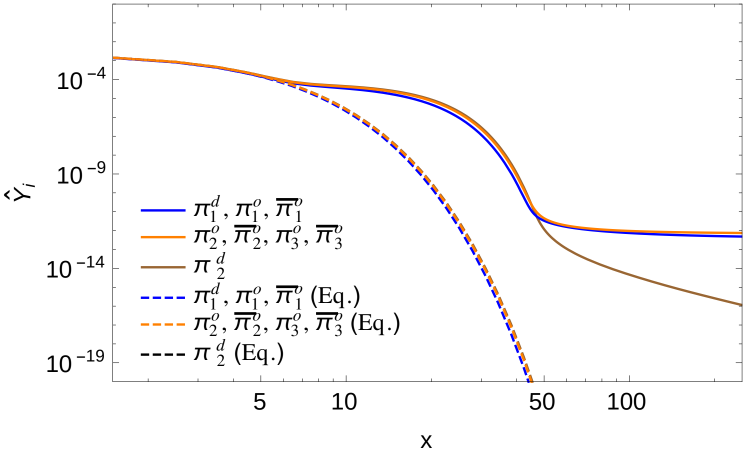
Applies to all categories

Category I: Cosmological evolution I



Coupling independent regime "Large" decay width

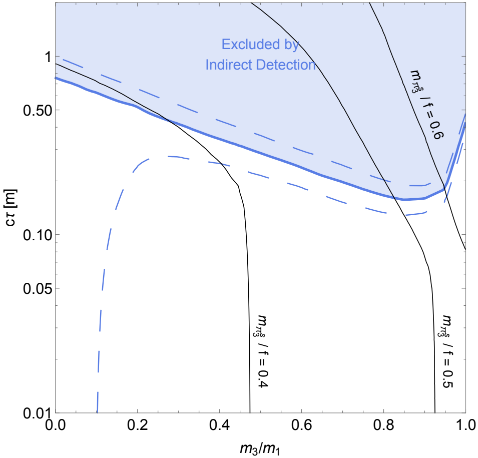
Category I: Cosmological evolution II



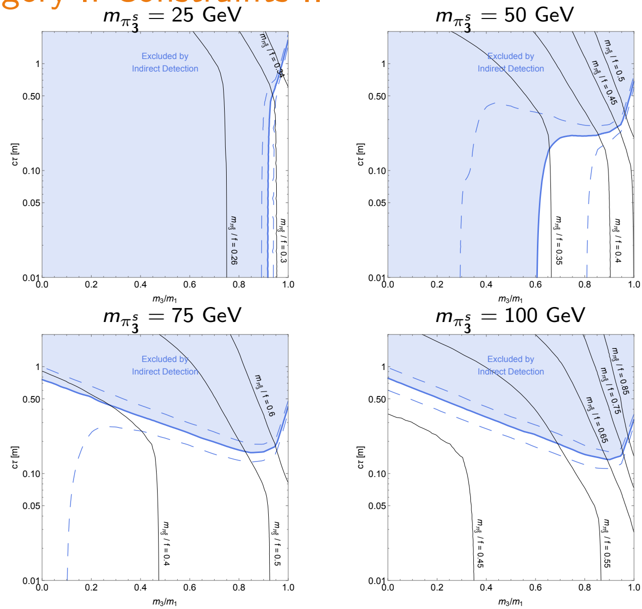
Codecaying regime "Small" decay width

Category I: Constraints I

$m_{\pi_3^s} = 75$ GeV

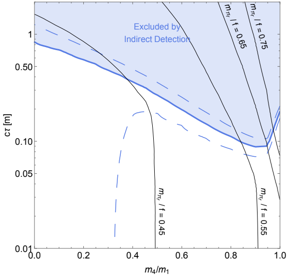


Category I: Constraints II

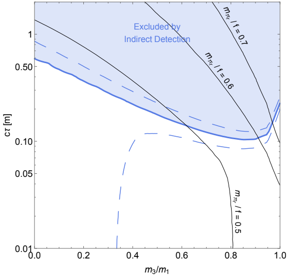


Category I: Constraints III

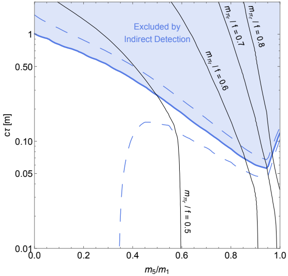
$SU(4) \times SU(4) \to SU(4) \to SU(3) \times U(1)$



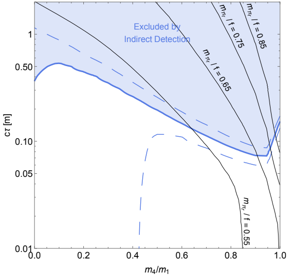
$SU(6) \to Sp(6) \to Sp(4) \times U(1)$



$SU(5) \times SU(5) \to SU(5) \to SU(4) \times U(1)$



$SU(8) \to Sp(8) \to Sp(6) \times U(1)$

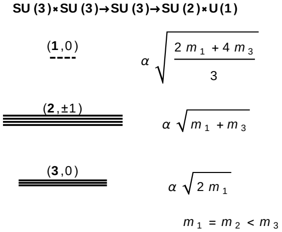


Category I: Summary

A structure of pions is said to belong to category I if, for each stable pion, there exist another stable pion with which it can annihilate to produce at least one unstable pion via a kinematically allowed $2 \to 2$ pion scattering process.

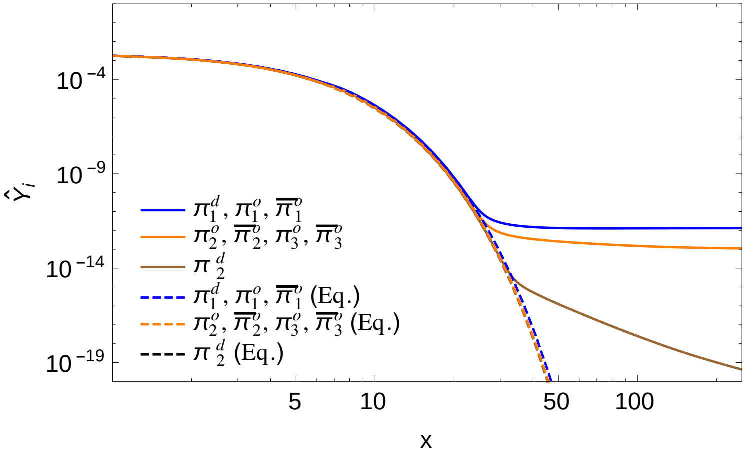
- Strongly constrained
- Will likely be even more constrained in the near future
- Upper limit on the decay length of $\mathcal{O}(1)$ m

Category II: Example



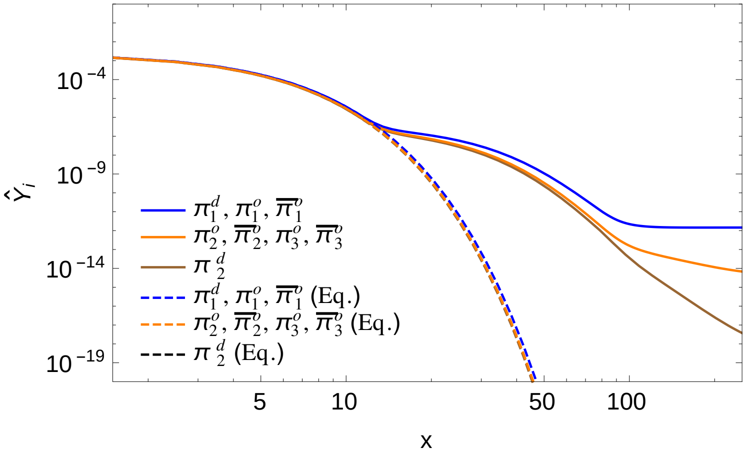
- $(\mathbf{3}, 0)$
  - Stable
  - Annihilation to unstable pions kinematically forbidden. $(\mathbf{3}, 0)X \to (\mathbf{1}, 0)Y$ forbidden for all X stable and all Y.
- $(\mathbf{2}, \pm 1)$
  - Stable
  - Annihilation to unstable pions kinematically allowed: $(\mathbf{2}, +1)(\mathbf{2}, -1) \to (\mathbf{3}, 0)(\mathbf{1}, 0)$
- $(\mathbf{1}, 0)$
  - Unstable

Category II: Cosmological evolution I



Coupling independent regime "Large" decay width

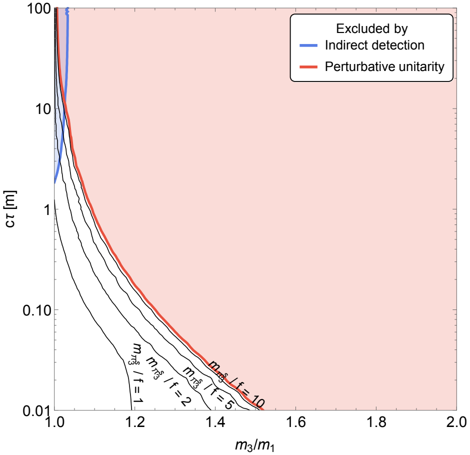
Category II: Cosmological evolution II



Codecaying regime "Small" decay width

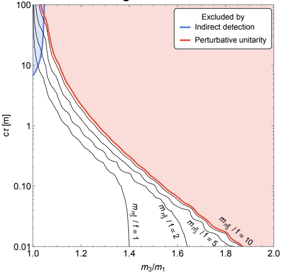
Category II: Constraints I

$m_{\pi_{\mathbf{3}}^s} = 75$ GeV

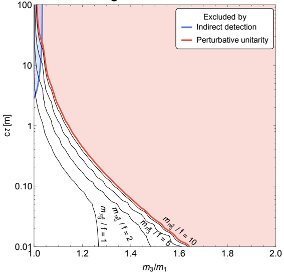


Category II: Constraints II

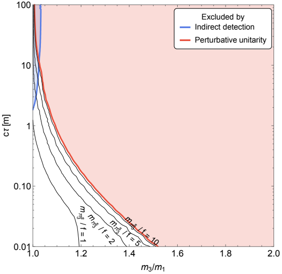
$m_{\pi_3^s} = 25$ GeV



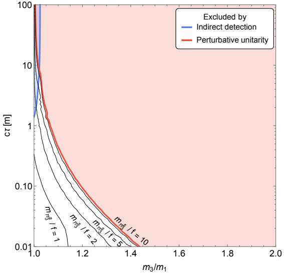
$m_{\pi_3^s} = 50$ GeV



$m_{\pi_3^s} = 75$ GeV

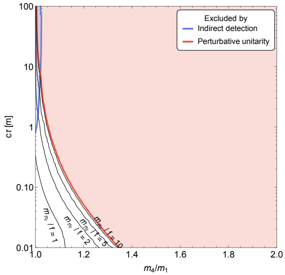


$m_{\pi_3^s} = 100$ GeV

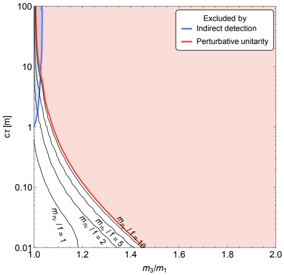


Category II: Constraints III

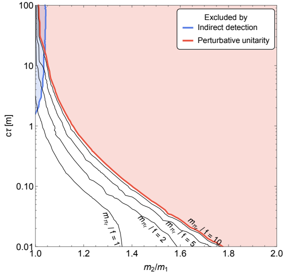
$SU(4) \times SU(4) \to SU(4) \to SU(3) \times U(1)$



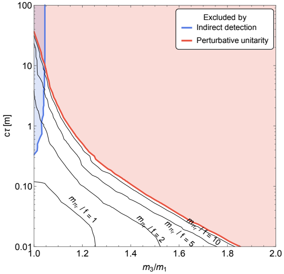
$SU(6) \to Sp(6) \to Sp(4) \times U(1)$



$SU(4) \to SO(4) \to U(1) \times U(1)$



$SU(5) \times SU(5) \to SU(5) \to SU(3) \times SU(2) \times U(1)$

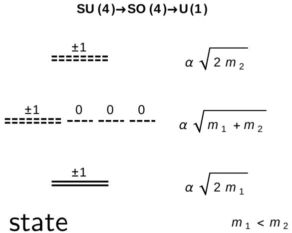


Category II: Summary

A structure of pions is said to belong to category II if, for some but not all of its stable pions, there exist another stable pion with which they can annihilate to produce at least one unstable pion via a kinematically allowed $2 \to 2$ pion scattering process.

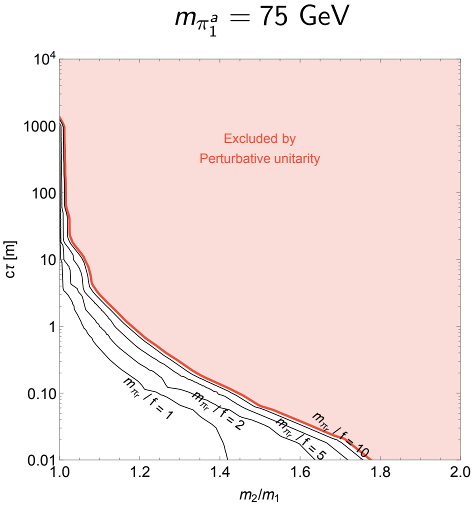
- Suppressed indirect detection constraints
- Upper limit on the decay length of $\mathcal{O}(10)$ m

Category III: Example



- Lightest charged state
  - Stable
  - Annihilation to unstable pions kinematically forbidden.
- All other states
  - Unstable

Category III: Constraints



Category III: Summary

A structure of pions is said to belong to category **III** if, for every stable pion, there does not exist another stable pion with which it can annihilate to produce at least one unstable pion via a kinematically allowed $2 \to 2$ pion scattering process.

- Essentially non-existant constraints from indirect detection
- Upper limit on the decay length of $\mathcal{O}(1000)$ m

Conclusion I

Main idea:

- The combination of spontaneous and explicit symmetry breaking determines a structure of dark pions.
- This structure determines which processes are kinematically forbidden or not.
- This determines the cosmology and the constraints.
- This determines what we can see at colliders.

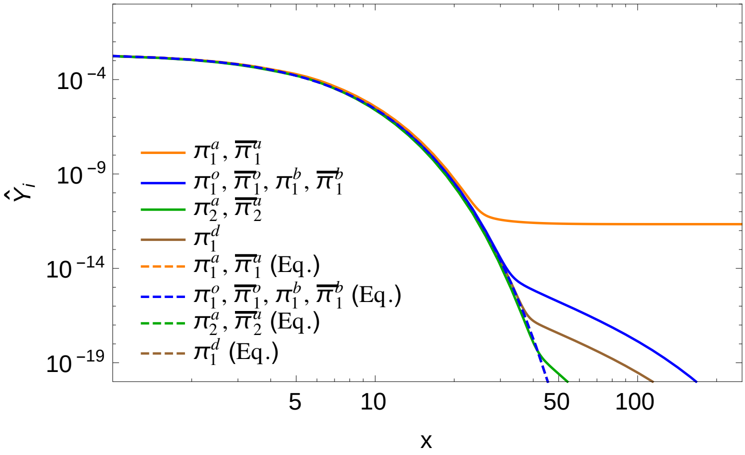
Conclusion II

Three categories of pion structures:

- Category I:
  - All stable pions contribute to indirect detection.
  - Strong constraints
  - Upper limit on the decay length of the pions of $\mathcal{O}(1)$ m
- Category II:
  - Only some of the stable pions contribute to indirect detection.
  - Reduced constraints
  - Upper limit on the decay length of the pions of $\mathcal{O}(10)$ m
- Category III:
  - No stable pions contribute to indirect detection.
  - Much reduced constraints
  - Upper limit on the decay length of the pions of $\mathcal{O}(1000)$ m

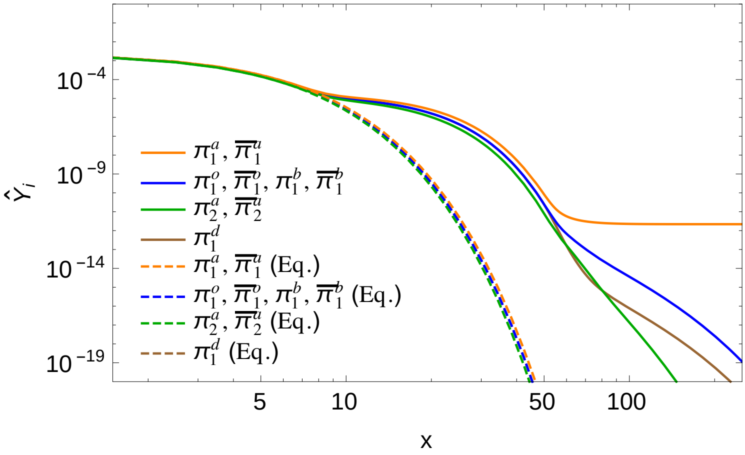
Backup slides

Category III: Cosmological evolution I



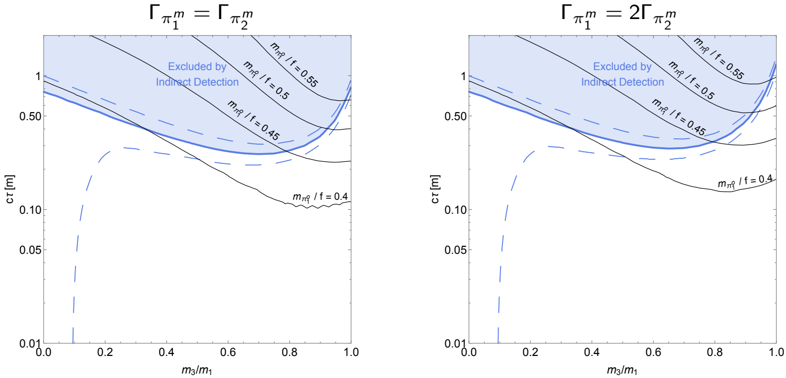
"Large" decay width

Category III: Cosmological evolution II

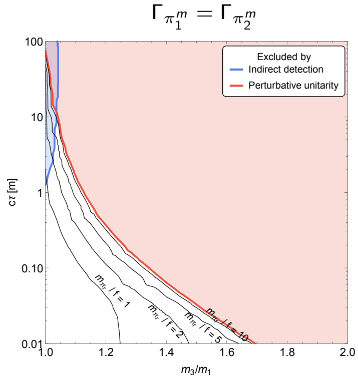


"Small" decay width

Category I: Two unstable pions



Category II: Two unstable pions



Examples

Cat.	Label	G	$\to$	H	$\to$	h	Condition(s)
I	CIa	$SU(3) \times SU(3)$	$\to$	$SU(3)$	$\to$	$SU(2) \times U(1)$	$m_1 = m_2 > m_3$
	CIb	$SU(6)$	$\to$	$Sp(6)$	$\to$	$Sp(4) \times U(1)$	$m_1 = m_2 > m_3$
	CIc	$SU(3) \times SU(3)$	$\to$	$SU(3)$	$\to$	$U(1) \times U(1)$	$m_1 > m_2 > m_3$
II	CIIa	$SU(4)$	$\to$	$SO(4)$	$\to$	$U(1) \times U(1)$	$m_1 < m_2$
	CIIb	$SU(3) \times SU(3)$	$\to$	$SU(3)$	$\to$	$SU(2) \times U(1)$	$m_1 = m_2 < m_3$
	CIIc	$SU(6)$	$\to$	$Sp(6)$	$\to$	$Sp(4) \times U(1)$	$m_1 = m_2 < m_3$
	CIId	$SU(5) \times SU(5)$	$\to$	$SU(5)$	$\to$	$SU(3) \times SU(2) \times U(1)$	$m_1 = m_2 < m_3 = m_4 = m_5$
	CIIe	$SU(4) \times SU(4)$	$\to$	$SU(4)$	$\to$	$SU(2) \times U(1) \times U(1)$	$m_1 = m_2 < m_3 \leq m_4$
III	CIIIa	$SU(4)$	$\to$	$SO(4)$	$\to$	$U(1)$	$m_1 < m_2$
	CIIIb	$SU(6)$	$\to$	$SO(6)$	$\to$	$U(1)$	$m_1 > m_2 > m_3,\ 2m_2 > m_1 + m_3$
	CIIIc	$SU(4) \times SU(4)$	$\to$	$SU(4)$	$\to$	$SU(2)$	$m_1 = m_2 > m_3 = m_4$

Table 1: Benchmark scenarios for the two categories of pion structures. The condition represents a relation that is assumed between the dark quark masses. It is sometimes crucial for the structure to be in a given category but not always. See Appendix B for more details.