Sp(4) gauge theory on the Lattice

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FWF
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Nature of Dark Matter (DM) unclear

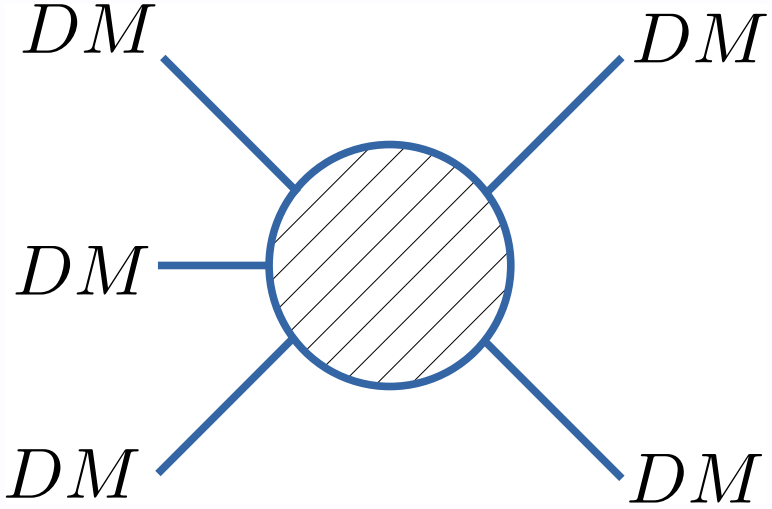
- Only gravitational effects observed
- Hypothesis: Particle Dark Matter
  - Coupling to Standard Model (SM) extremely weak
  - Stable over tens of billions of years
- Density distribution of DM constrains theories!

Dark matter as a thermal relic

- Thermal equilibrium in early Universe
  - Dark Matter particles deplete as Universe cools
  - At some T: DM and SM decouple ("freeze out")
- Relevant depletion process constrains DM!
- Example: **WIMPs**
  - deplete by 2 DM $\rightarrow$ 2 SM
  - Masses typically around $\mathcal{O}(1\ \mathrm{TeV})$

Strongly Interacting Massive Particles (SIMPs)

- Depletion by **3 DM $\rightarrow$ 2 DM**
- Requires additional mediator for SM-equilibrium
- Masses typically around $\mathcal{O}(100\ \mathrm{MeV})$
- Need a mechanism that can provide **3 DM $\rightarrow$ 2 DM**



[1402.5143, 1411.3727, 1512.07917]

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

- Chiral symmetry breaking with ≥ 5 Goldstones
- 5-point interaction $\mathcal{L}_{\mathrm{WZW}}$ between Goldstones Π

$$\mathcal{L}_{\mathrm{WZW}} \propto \epsilon^{\mu\nu\rho\sigma} \mathrm{Tr}[\Pi \partial_\mu \Pi \partial_\nu \Pi \partial_\rho \Pi \partial_\sigma \Pi]$$

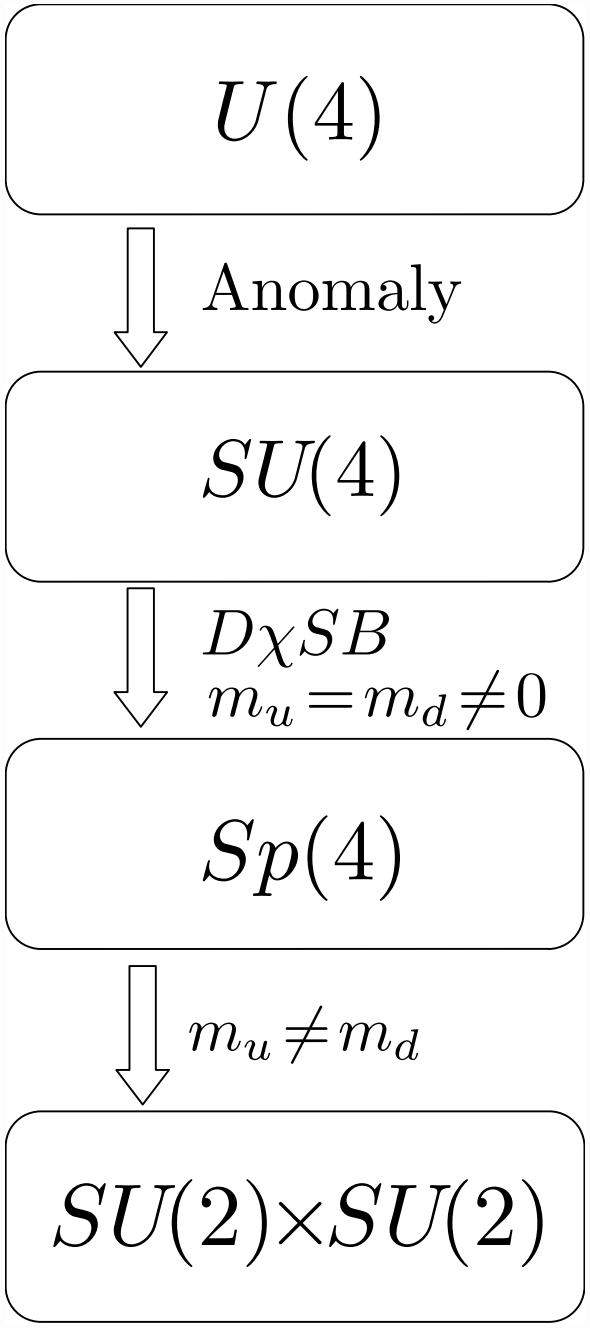
Idea: Gauge theory with $\mathcal{L}_{\mathrm{WZW}}$ in EFT and
Goldstones as Dark Matter candidates
(+ mediator to SM)

$Sp(4)$ gauge theory as a SIMP model

- $N_f = 2$ fundamental sufficient for WZW Term
- Massive fermions u, d, so that Π are massive
- Introduce small mass difference between Fermions
  - Allows hierarchy: One Π is lighter than the others

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{u}(i \not{D} + m_u) u + \bar{d}(i \not{D} + m_d) d$$

$$m_d = m_u + \Delta m$$



Global Symmetries

- Chiral symmetry breaking: $SU(4)_F \rightarrow Sp(4)_F$
- 5 pseudo-Goldstone bosons
- $m_u \neq m_d$ breaks symmetry further
- Same pattern for all symplectic groups

[hep-ph/0001171,1205.4205]

Particle content of the theory

- 5 pseudo-Goldstones Π, 10 vectors P, ...
- No baryons (for any $Sp(N)_c$ group)
- Glueballs heavier than mesons
- $m_u \neq m_d$ lifts degeneracy

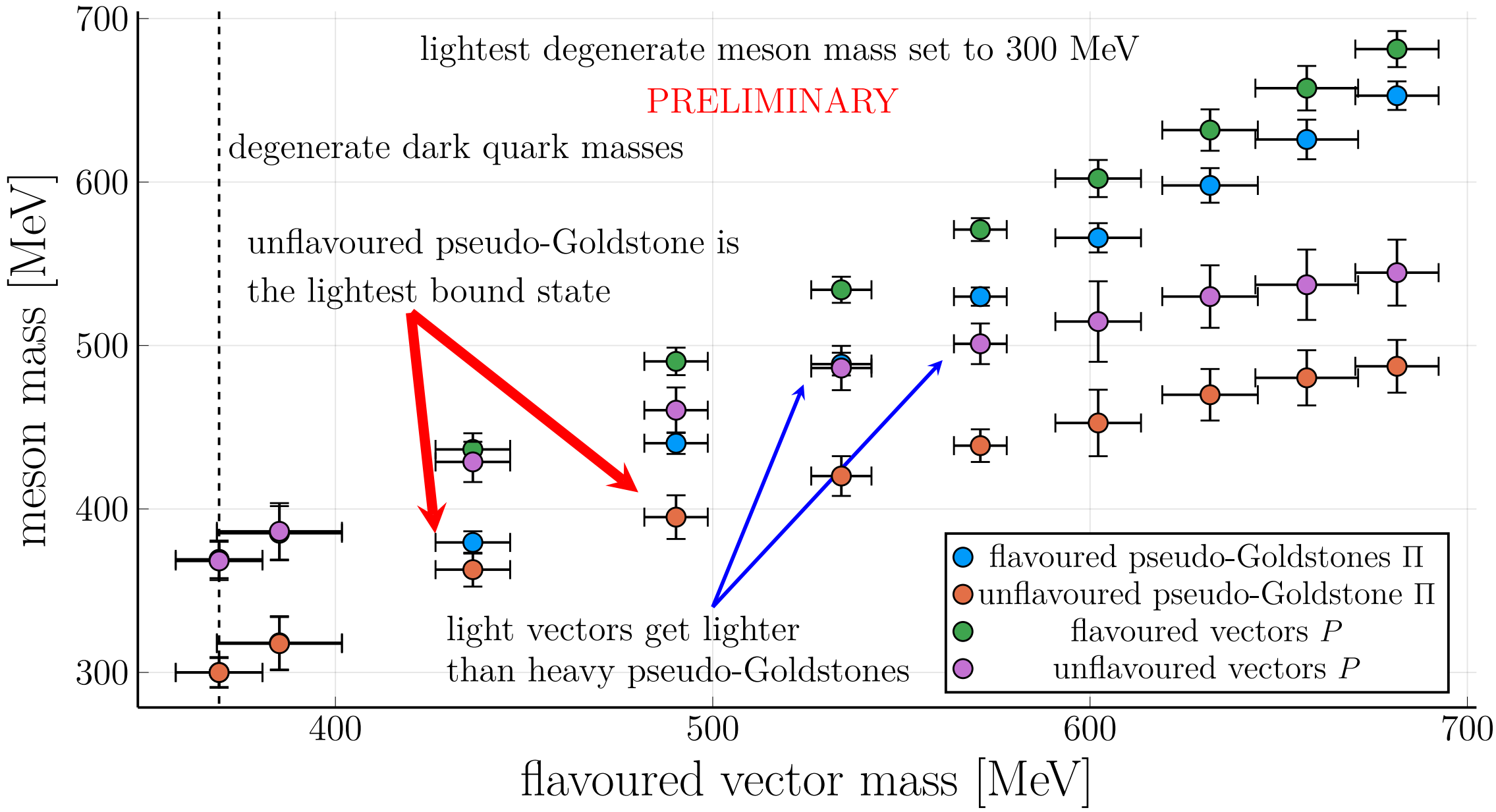
$$5\Pi \to 4\Pi(\text{flavoured}) + 1\Pi(\text{unflavoured})$$

$$10P \to 4P(\text{flavoured}) + 6P(\text{unflavoured})$$

- **What is the hierarchy of the mesons masses?**

[1712.04220, 1909.12662] [Kulkarni et. al. (in preparation)]

Sp(4) Nf=2 : pseudo-Goldstones' Π and iso-non-singlet vector mesons' P masses



Summary

- Mesonic spectrum of $Sp(4)$ with $N_f = 1 + 1$
- Strong isospin-splitting in non-$SU(N)$ theory
  - 5 Pseudo-Goldstones are **not** degenerate
  - **Lightest state: Unflavoured Pseudo-Goldstone**
  - Large Δm: *Unflavoured Vectors relevant*

Outlook

- On the lattice:
  - Additional channels (axialvectors, tensors, ...)
  - More low energy constants (chiral condensate,...)
  - scattering processes: $2 \to 2$ and $3 \to 2$

Coupling to the SM, consequences for **cosmology, astrophysics, direct detection** and **collider searches** within the FWF funded **research group FG1**

References (1/2)

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- [0805.2058]Del Debbio, Patella, Pica. Phys.Rev.D 81, 2010
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- [1402.5143] Hochberg, Kuflik, Volansky, Wacker. Phys.Rev.Lett. 113, 2014

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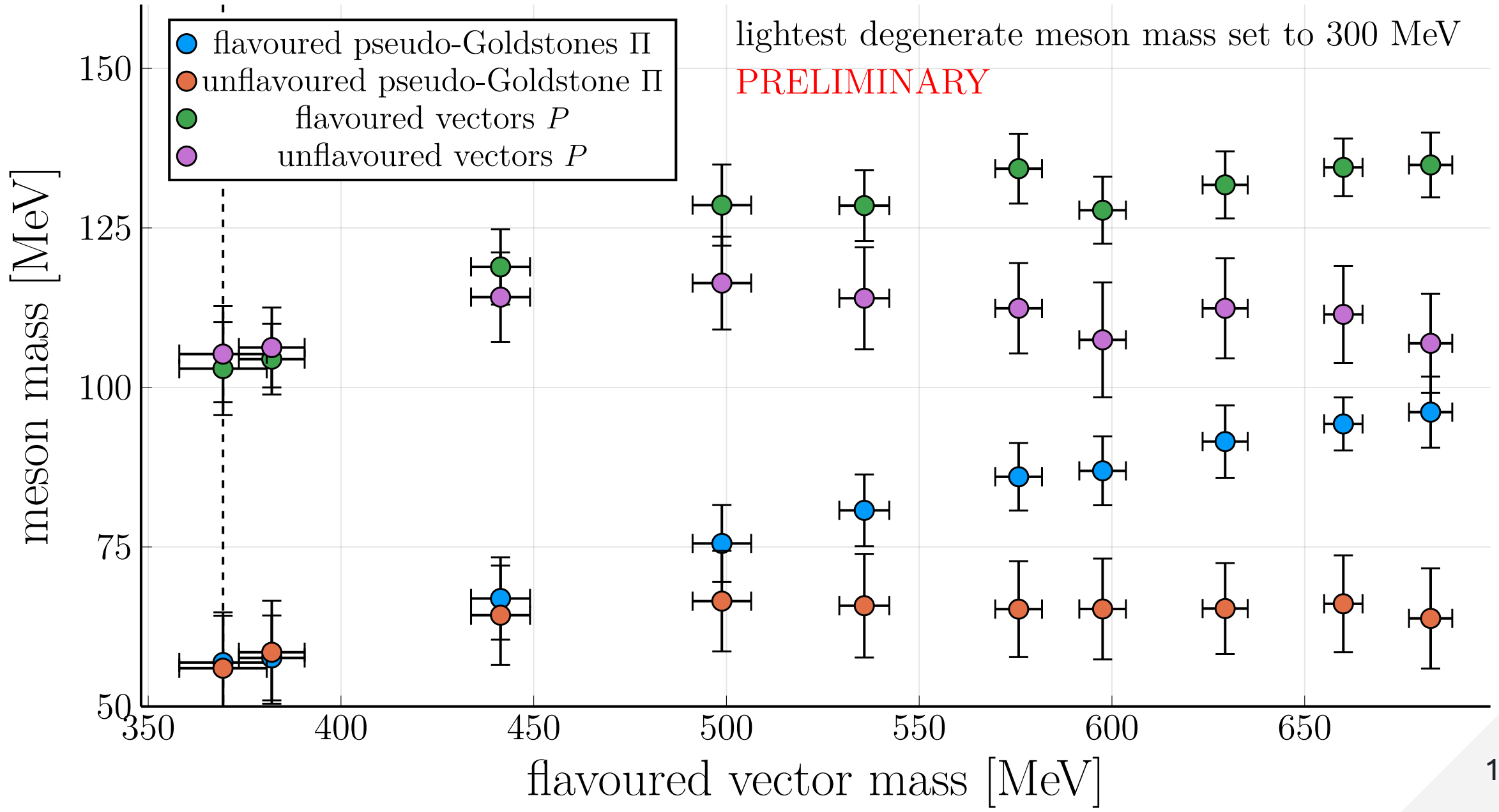
- [1411.3727] Hochberg, Kuflik, Murayama, Volansky, Wacker. Phys.Rev.Lett. 115, 2015
- [1512.07917] Hochberg, Kuflik, Murayama. JHEP05, 2016
- [1712.04220] Bennett, Hong, Lee, Lin, Lucini, Piai, Vadacchino. JHEP03, 2018
- [1909.12662] Bennett, Hong, Lee, Lin, Lucini, Piai, Rantaharju, Vadacchino. JHEP12, 2019
- [Kulkarni et. al.] Kulkarni, Maas, Mee, Nikolic, Pradler, Zierler (in preparation)

Back-up Slides

Sp(4) Nf=2 : Π and P decay constants



$SU(3)$ vs. $Sp(4)$

- in case of $N_f = 2$
- $Sp(N)$ always larger
- general property of pseudo-real and complex fermion representation