Revised phenomenology of new physics particles in GeV mass range

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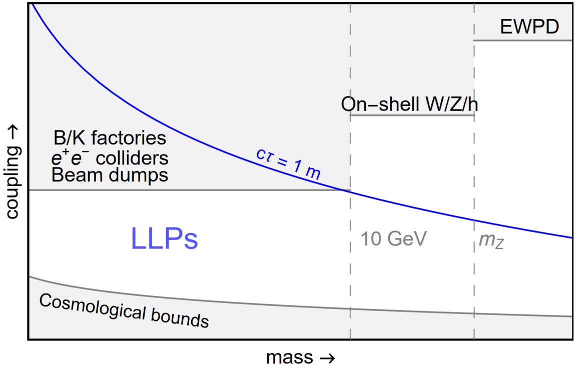
Introduction

New physics in the GeV mass range:

- May be capable of solving BSM problems
- May be extensively probed in the lab
- Lab and cosmic probes are complementary



Do we understand their phenomenology well enough?

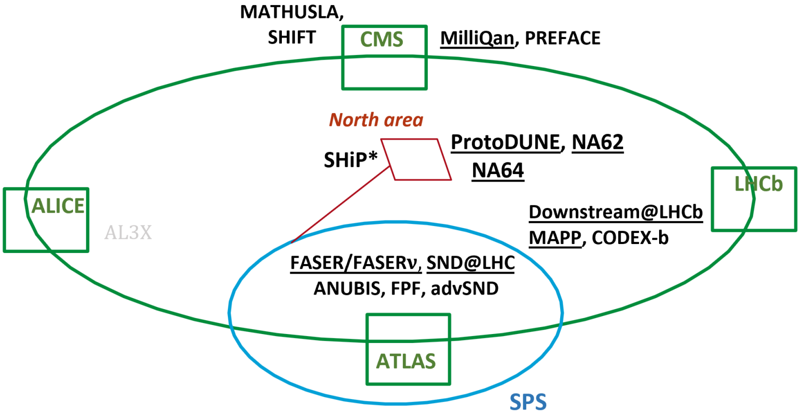
GeV-mass particles: examples I

Model	***(Effective) Lagrangian***	***What it looks like***
HNL $\boldsymbol{N}$	$Y\bar{L}\tilde{H}N + \text{h.c.}$	Heavy neutrino with interaction suppressed by $U \sim \frac{Yv_h}{m_N} \ll 1$
Higgs-like scalar $\boldsymbol{S}$	$c_1 H^\dagger H S^2 + c_2 H^\dagger H S$	A light Higgs boson with interaction suppressed by $\theta \sim \frac{c_2 v_h}{m_h} \ll 1$
Vector mediator $\boldsymbol{V}$	$-\frac{\epsilon}{2} B_{\mu\nu} V^{\mu\nu} + g V^\mu J_{\mu,B}$	A massive photon/vector meson with interaction suppressed by $\epsilon, g \ll 1$
ALP $\boldsymbol{a}$	$c_G \frac{\alpha_s}{4\pi} a G^{\mu\nu} \tilde{G}_{\mu\nu} + \dots$	A $\pi^0/\eta/\eta'$-like particle with interaction suppressed by $\frac{f_\pi}{f_a} \ll 1$
...	...	...

GeV-mass particles: examples II

Model	***(Effective) Lagrangian***	***What it looks like***
MCPs χ	$\kappa e\bar{\psi}\gamma^{\mu}\psi A_{\mu}$	Millicharged particle
Quasi-elastic DM χ	$g_d\bar{\chi}\gamma_{\mu}\chi V^{\mu}$	Stable particles coupled via dark photons V
Inelastic dark matter χ', χ	$g_d\bar{\chi}'\gamma_{\mu}\chi V^{\mu} + \text{h.c.}$	An unstable particle χ' decaying into $\chi + \text{SM}$
Dark QCD ρ_d/π_d	$\bar{q}_d\gamma^{\mu}q_d Z'_{\mu} + \ldots$	A dark photon/ALP with additional production in showerings
...	...	...

GeV-mass particles: examples III



GeV-mass particles: one of the goals of intensity frontier experiments

Challenge: phenomenology description I

Main challenge of phenomenology description – mixing with mesons

– Interaction Lagrangian of a new physics particle X:

$$\mathcal{L} = X^a \cdot \mathcal{O}_a[\psi_{\rm SM}] + X^a X^b \cdot \mathcal{O}_{ab}[\psi_{\rm SM}] + \dots \tag{1}$$

– Expansion of $\mathcal{O}_a[\psi_{\rm SM}]$ in terms of bound states $\mathcal{Y}$:

$$\mathcal{O}_a = \overbrace{c_1(\mathcal{Y}, \partial\mathcal{Y}, \partial^2\mathcal{Y})_a}^{\text{1-particle}} + \overbrace{c_2(\mathcal{Y}^2, (\partial\mathcal{Y})^2, \mathcal{Y}\partial\mathcal{Y})_a}^{\text{2-particle}} + \dots \tag{2}$$

– $X^a\mathcal{Y}_a$ – induced resonant mixing. Every process with $\mathcal{Y}$ may involve X by replacing

$$\psi_{\mathcal{Y}} \to \theta_{\mathcal{Y}X}\psi_X, \quad \theta_{\mathcal{Y}X} = \frac{c_1}{m_X^2 - m_{\mathcal{Y}}^2 - i m_{\mathcal{Y}}\Gamma_{\mathcal{Y}}} + \dots \tag{3}$$

Challenge: phenomenology description II

Main challenge – mixing with mesons

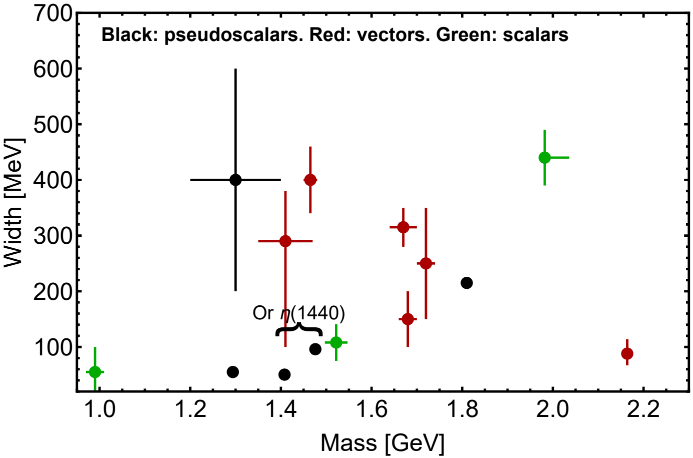
LLP	**Mixing with $\mathcal{Y}$**
Dark photon/dark $\boldsymbol{\rho}$	$\boldsymbol{\rho^0, \omega, \phi}$ and their excitations
$\boldsymbol{V}$ coupled to $\boldsymbol{J_B^\mu}$	$\boldsymbol{\omega, \phi}$ and their excitations
Higgs-like scalar	$\boldsymbol{f_0}$ and its excitations
ALP/dark π	$\boldsymbol{\pi^0, \eta, \eta'}$ and their excitations
HNL	No mixing

- Most of the "simplest" models introduce mixing
- To understand their interaction, it is necessary to carefully know the meson spectroscopy in the mass range $\boldsymbol{M \lesssim 2}$ **GeV**

Challenge: phenomenology description III

Meson spectroscopy

- Poorly measured masses and widths for some mesons
- Interpretation is ambiguous:
  - One meson or two mesons?
  - 2-quark or 4-quark bound states?
- This is important when embedding them into SU(3) representations

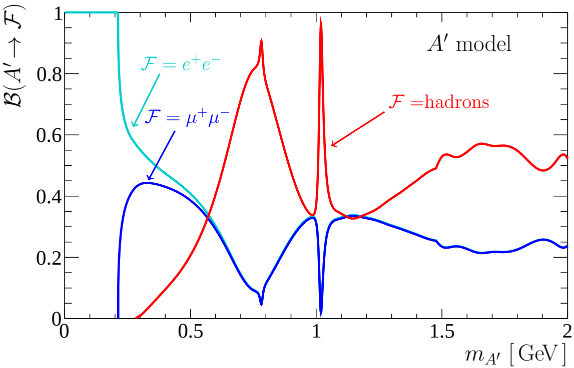


pdg, [2407.18348]

Challenge: phenomenology description IV

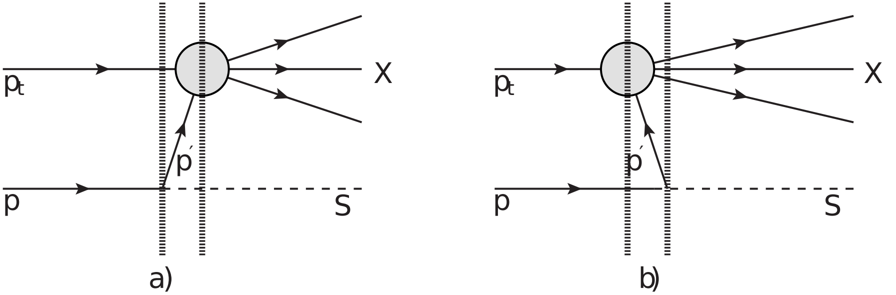
Example 1 – dark photons:

- Decay rates: may be extracted from $\boldsymbol{e^+e^-} \to$ **hadrons**
- $\mathcal{O}(20\%)$ uncertainty in hadronic widths
- Resonant features in decay widths: result of the mixing with vector mesons



[1801.04847]

Challenge: phenomenology description V



– Production modes: no opportunity to directly use real data. Mixing contributes to proton bremsstrahlung and fragmentation

– Quasi-real approximation: $\sigma_{pp\to V+X} \approx \int d\Phi P_{p\to p'V} \times \sigma_{pp\to X}$ (parametrized by the virtuality of p')

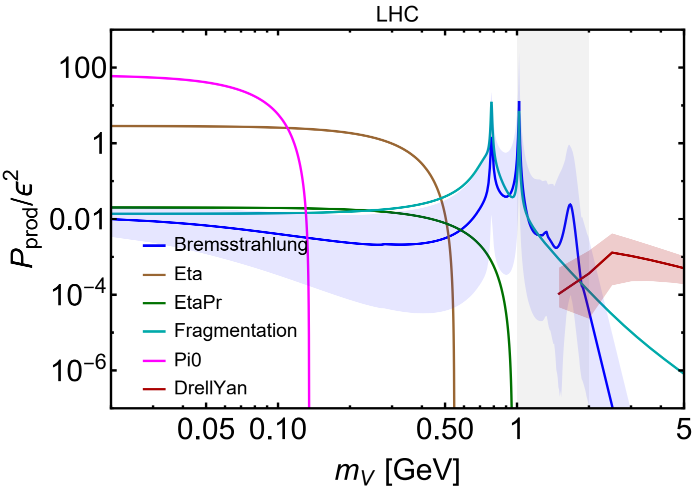
– Proton EM form-factor in the timelike region $F_p^{(1,2)}(q^2 > 0)$: where the mixing enters

Challenge: phenomenology description VI

- Unitary analytic model:

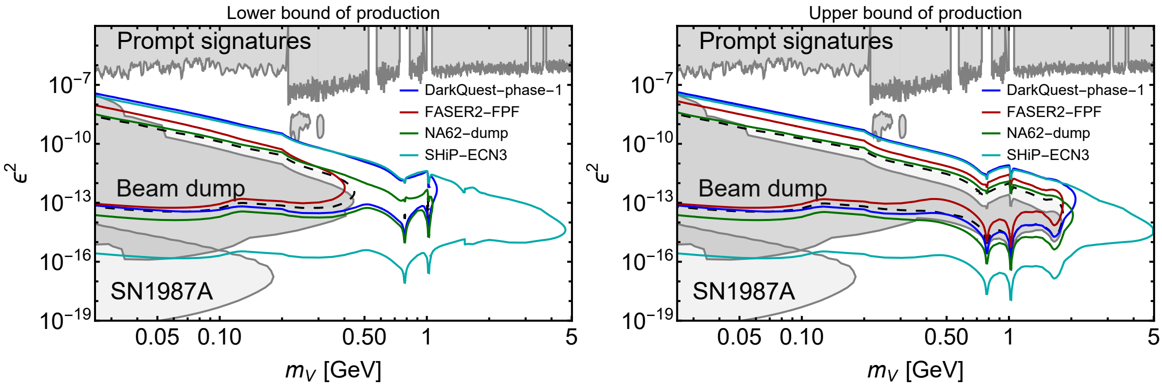
$$F_p^{(1,2)}(q) = \sum_i \frac{f_i m_{V_i}^2}{q^2 - m_{V_i}^2 - i\Gamma_{V_i} m_{V_i}}$$

- Significant uncertainties in the production – orders of magnitude!



[2504.06828], [2409.11096]

Challenge: phenomenology description VII



– Uncertainties heavily change the parameter space of dark photons – both in terms of mass and coupling!

[2409.11096]

Challenge: phenomenology description VIII

Example 2 – hadronically coupled ALPs:

$$\boldsymbol{\mathcal{L}_a = c_G \frac{\alpha_s}{4\pi}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{\partial_\mu a}{f_a}\sum_q c_q \bar{q}\gamma^\mu\gamma_5 q + \text{flavor-changing}} \tag{4}$$

1. Perform the chiral rotation

$$\boldsymbol{q \to e^{-i\gamma_5 c_G \kappa_q a/f_a} q}, \quad q = u, d, s \tag{5}$$

   with $\mathbf{tr}[\boldsymbol{\kappa_q}] = \mathbf{1}$
   It converts the gluonic coupling into the second term of Eq. (6)
2. Make a correspondence between the resulting theory and ChPT Lagrangian $\boldsymbol{\mathcal{L}}_{\mathbf{ChPT+a}}[\boldsymbol{\kappa_q}]$ [2012.12272]
3. Supplement the interactions with phenomenological Lagrangians describing interactions with other mesons ($\boldsymbol{\rho, K_0, f_2}$, etc.)

Challenge: phenomenology description IX

Unlike dark photons, no data allows direct extraction of ALP decay rates

- Heavy pseudoscalar mesons $\boldsymbol{P_h}$:

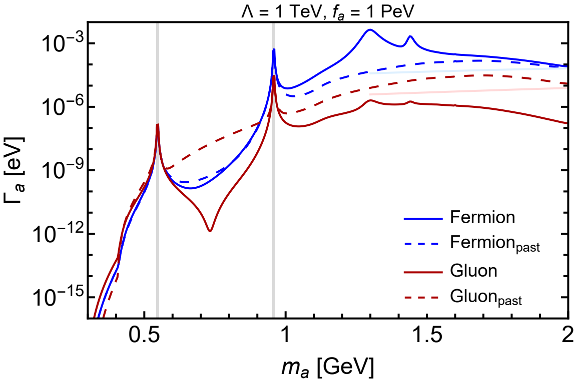
Resonance	$\boldsymbol{\eta(1295)}$	$\boldsymbol{\pi^0(1300)}$	$\boldsymbol{\eta(1405/1475)^*}$	$\boldsymbol{\pi^0(1800)}$
Mass [GeV]	1.294	1.3	1.408/1.476	$1.9 \cdot 10^{-4}$
Width [MeV]	55	200 – 600	50/96	215

*: *may be interpreted as a single* $\boldsymbol{\eta(1440)}$

- Some of $\boldsymbol{P_h}$s are very narrow and hence cannot be “averaged out”
- Previous studies did not consider the ALP mixing with $\boldsymbol{P_h}$ *[1811.03474], [2110.10691], [2310.03524]*

Challenge: phenomenology description X

- To include the mixing, we used the Extended Linear Sigma Model (ELSM) *[2407.18348]*, *[1612.09218]*
- Effect of P_h on decay rates: $\mathcal{O}(1)$ for c_G contributions* and orders of magnitude for c_q contributions



- Issue: ambiguity in the description [1612.09218] has hardly quantifiable impact on the ALP rates

*: *effect of close cancellation of mixing and multi-field contributions*

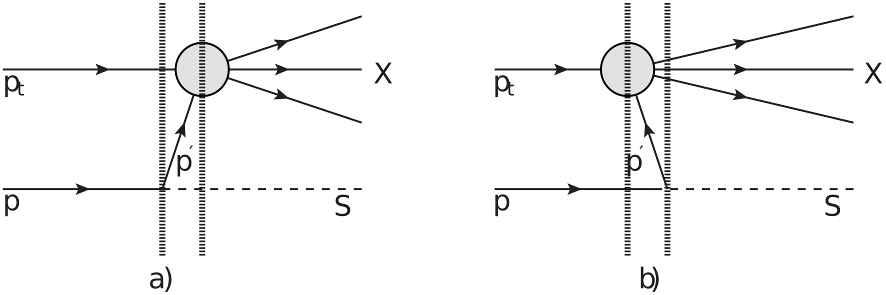
[2501.04525]

Conclusions

- GeV-mass new physics particles are one of the target goals of intensity frontier experiments
- Experimental opportunities to explore their parameter space meet theoretical challenges
- One of the most important challenges: mixing with mesons
- Depends on the progress of meson spectroscopy

Backup slides

Proton bremsstrahlung [2409.09123], [2409.11096]



- Quasi-real approximation: $\boldsymbol{\sigma_{pp\to V+X} \approx \int d\Phi P_{p\to p'V} \times \sigma_{pp\to X}}$ (parametrized by the virtuality of $\boldsymbol{p'}$)
- Additional source of uncertainty: proton EM form-factor in the timeline region

More on hadronically coupled ALPs I

ALP Lagrangian:

$$\boldsymbol{\mathcal{L}_a = c_G \frac{\alpha_s}{4\pi}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{\partial_\mu a}{f_a}\sum_q c_q \bar{q}\gamma^\mu\gamma_5 q + \textbf{flavor-changing}} \tag{6}$$

1. Perform the chiral rotation

$$\boldsymbol{q \to e^{-i\gamma_5 c_G \kappa_q a/f_a} q}, \quad q = u, d, s \tag{7}$$

   with $\boldsymbol{\mathrm{tr}[\kappa_q] = 1}$
   It converts the gluonic coupling into the second term of Eq. (6)
2. Make a correspondence between the resulting theory and ChPT Lagrangian $\boldsymbol{\mathcal{L}_{\mathrm{ChPT+a}}[\kappa_q]}$ [2012.12272]

– Supplement the interactions with phenomenological Lagrangians describing interactions with other mesons ($\boldsymbol{\rho, K_0, f_2}$, etc.)

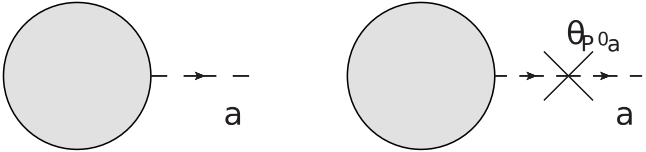
More on hadronically coupled ALPs II

– The ALP-ChPT Lagrangian implies **mixing** of ALPs with pseudoscalar mesons $\boldsymbol{P^0 = \pi^0, \eta, \eta'}$:

$$\boldsymbol{P^0 \to P^0 + \theta_{P^0 a} a, \quad \theta_{P^0 a} = \frac{f(m_{P^0}, m_a)}{m_{P^0}^2 - m_a^2 - i m_{P^0}\Gamma_{P^0}} + g(\kappa_q) + \dots} \tag{8}$$

Phenomenologically, a light ALP is an admixture of $\boldsymbol{P^0}$s

More on hadronically coupled ALPs III



- Resulting Lagrangian must predict κ_q-independent observables [2102.13112] and include all pseudoscalar excitations
- In practice: cancellation of κ_q contribution from the ALP-meson mixing (right) and many-field interactions (left)
- Widely adopted descriptions [1811.03474], [2201.05170], [2305.01715]: many-field κ_q-terms were missing in production and decay rates

ELSM I

- Extended linear sigma model (ELSM) [2407.18348], [1612.09218]
- ELSM adds a heavy pseudoscalar octet and identifies the “flavorless” excitations with $\boldsymbol{\pi^0(1300), \eta(1295), \eta(1440)}$
- ALPs may be added to ELSM Lagrangian completely similarly to the ChPT case

ELSM II

Incompleteness of ELSM and limited knowledge of properties of heavy excitations [2407.18348]:

- Ref. [1612.09218] dropped various operators with heavy pseudoscalars that may severely contribute to the c_G terms
  - Including them, however, requires full re-analysis of the ELSM fit to data
  - A study including these terms: in preparation
- $\pi^0(1300)$ has poorly measured width
- It is not clear whether the $\eta(1295/1440)$ are 2-quark bound states or also include 4-quark admixtures