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On Higgs decay to a photon and a massless dark photon

Cheng-Wei Chiang
National Taiwan University
National Center for Theoretical Sciences

Hugues Beauchesne and CWC, PRL 130 (2023) 14, 141801; PRD 108 (2023) 1, 015018

Motivations for Dark Photon

- The dark photon, denoted by A', is a hypothetical Abelian gauge boson that can in principle mix with the photon, denoted by A.

Holdom 1986

- It can act as a portal to a dark sector or introduce dark matter self-interactions that can potentially solve the small-scale structure problems and the XENON1T anomaly.

Spergel, Steinhardt 2000
XENON1T 2020
CWC, Lu 2020

- Depending on its decoupling temperature during the evolution of the Universe, the dark photon can affect the big bang nucleosynthesis by altering the effective number of thermally excited neutrino degrees of freedom.

Dobrescu 2005
Fradette, Pospelov, Pradler, Ritz 2014

- The dark photon may also modify the stellar energy transport mechanism and thus the cooling of, for example, neutron stars.

CWC, Lu 2022

Collider Searches of Dark Photon

- A potential discovery channel of the dark photon that has received considerable attention is the decay of the Higgs boson to a photon and a massless dark photon, $h \to AA'$.

- The interest in this channel stems in large part from early phenomenological studies, which indicated that $\mathrm{BR}(h \to AA') \leq 5\,\%$ was at the time compatible with experimental constraints. Gabrielli, Heikinheimo, Mele, Raidal 2014
➠ this has motivated several collider searches of the channel (through VBF and ZH productions) CMS 2019, 2021 ATLAS 2022
➠ is this theoretical estimate too optimistic?

- Presently, the most precise collider bound on this branching ratio comes from ATLAS, which uses $139\ \mathrm{fb}^{-1}$ of integrated luminosity at a center-of-mass energy of $13\ \mathrm{TeV}$, giving $\mathrm{BR}(h \to AA') \leq 1.8\,\%$ at 95% CL. ATLAS 2022

Usual Dark Photon

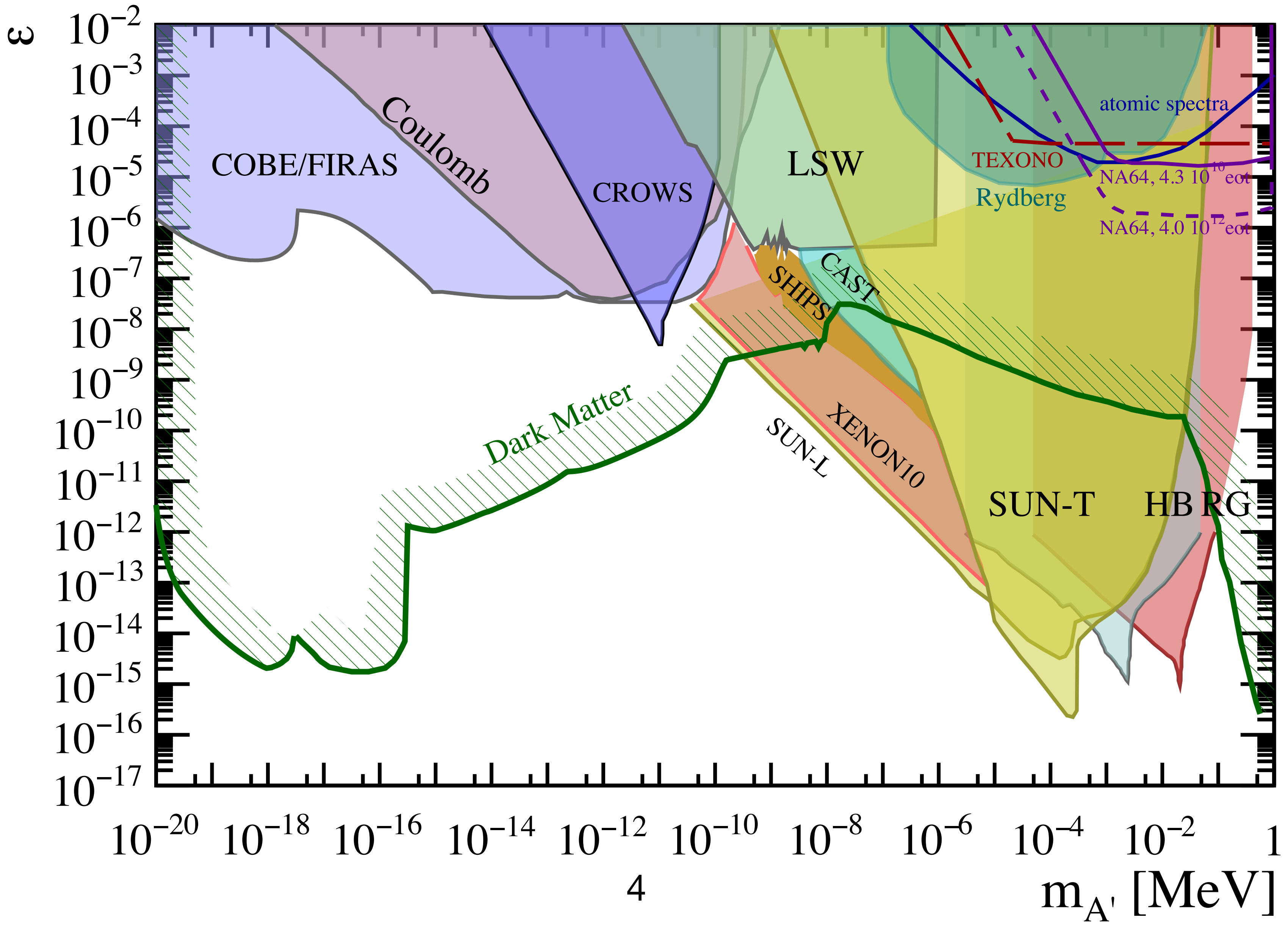
- In principle, SM particles themselves could interact at tree level with the dark photon, due to kinematic mixing between the weak hypercharge and the gauge boson of a new $U(1)'$ gauge group

- The problem with this scenario is that $\mathrm{BR}(h \to AA)$ is determined to be small and that interactions between SM particles and such a dark photon have been constrained by other processes to be very small.

  ➠ $\mathrm{BR}(h \to AA')$ would be too small for LHC to probe

Curtin, Essig, Gori, Shelton, 2015
Fox, Low, Zhang 2018
Pan, He, He, Li 2020

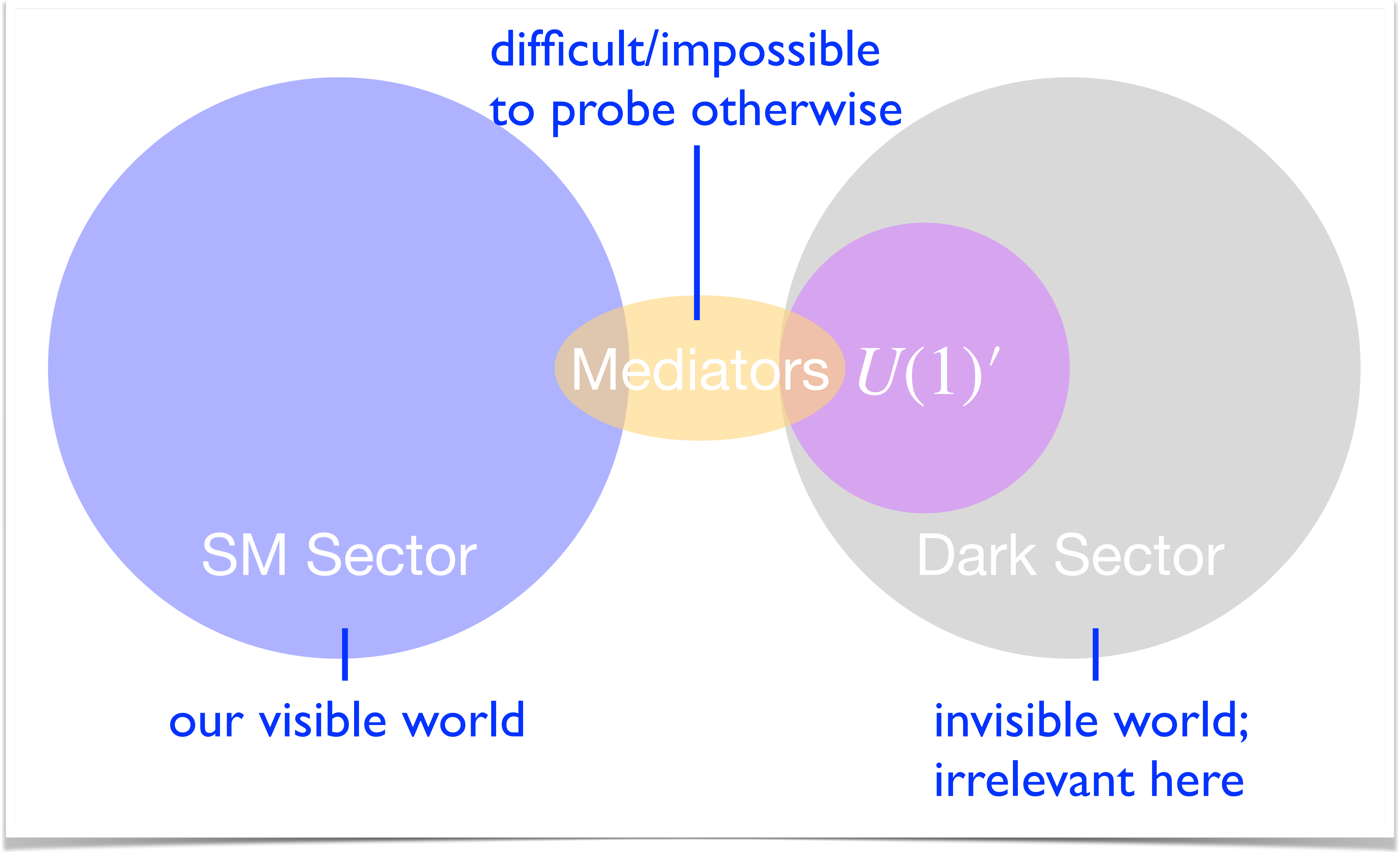
ε is defined to be the suppression factor of the $U(1)'$ gauge coupling to the $U(1)_{\mathrm{EM}}$ gauge coupling e —



Fabbrichesi, Gabrielli, Lanfranchi 2020

Scenario to Study

- A potentially discoverable $\mathrm{BR}(h \to AA')$ requires the introduction of new particles that can mediate between the SM sector and the dark photon.



- An observation of $h \to AA'$ would not only verify the existence of the dark photon, but also provide indirect evidence of more new particles.

Assumptions

- Assume a new exact $U(1)'$ gauge group whose gauge boson is A' and that all SM particles are neutral under this group.
- Assume a set of mediators charged under both SM gauge groups and the $U(1)'$.
- Such mediators and their interactions satisfy the following conditions:

(1) The Lagrangian is renormalizable and preserves all the gauge symmetries.

(2) The Higgs decay to AA' can occur at one loop.

(3) The mediators are neutral under QCD.

(4) The mediators are either complex scalars or vector-like fermions.

(5) There are no more than two new fields.

(6) No mediators have a nonzero expectation value or mix with SM fields.

Objectives

- Though not completely model-independent, our study covers a wide class of generic models based on the above-mentioned assumptions.
- They illustrate why building models that lead to a sufficiently large $\mathrm{BR}(h \to AA')$ under various existing constraints will be extremely challenging.
- In this study, we consider constraints from the Higgs signal strengths, electroweak precision tests, the electron electric dipole moment (eEDM), unitarity, and perturbativity.
- We can put constraints on mediators that enable the $h \to AA'$ decay.
- We demonstrate that these constraints restrict its BR to values considerably lower than current collider limits.

Five Generic Interaction Classes

- The above assumptions imply that the Lagrangian has to contain a term coupling the Higgs doublet to mediators at tree level.
- There are only five classes of generic forms (one fermion class and four scalar classes) that such a term can take while respecting our assumptions.
- Schematically, they are (all indices suppressed):

SM Higgs doublet

Fermion:

$$\overline{\psi}_1 \left(A_L P_L + A_R P_R\right) \psi_2 H + \text{ H.c.},$$

chiral couplings

For more explicit forms, please see our paper.

Scalar:

$$\text{I: } \mu \phi_1^\dagger \phi_2 H + \text{ H.c.}, \qquad \text{II: } \lambda H^\dagger H \phi^\dagger \phi,$$

$$\text{III: } \lambda H^\dagger H \phi_1^\dagger \phi_2 + \text{ H.c.}, \qquad \text{IV: } \lambda H H \phi_1^\dagger \phi_2 + \text{ H.c.},$$

Will consider one model at a time for the sake of definiteness and manageability

For each class, the fields can take different quantum numbers to form classes of models.

Fermionic Model

- Consider a pair of vector-like fermions ψ_1 and ψ_2 that transforms as follows:

Field	$SU(2)_L$ dimension	weak hypercharge	$U(1)'$ charge
ψ_1	$p = n \pm 1$	$Y^p = Y^n + 1/2$	Q'
ψ_2	n	Y^n	Q'

- The Lagrangian that determines the masses of the fermions is

Yukawa couplings; generally complex, with a relative phase leading to CPV

$$\mathcal{L}_m = -\left[\sum_{a,b,c} \hat{d}^{pn}_{abc} \bar{\psi}^a_1 \left(A_L P_L + A_R P_R\right) \psi^b_2 H^c + \text{ H.c.}\right] - \mu_1 \bar{\psi}_1 \psi_1 - \mu_2 \bar{\psi}_2 \psi_2,$$

— $SU(2)_L$ indices, summed over the multiplets

where by gauge invariance we have uniquely

$$\hat{d}^{pn}_{abc} = \langle j_1 j_2 m_1 m_2 \mid JM \rangle$$ — Clebsch-Gordan coefficient

and

$$J = \frac{p-1}{2}, \quad j_1 = \frac{n-1}{2}, \quad j_2 = \frac{1}{2}, \quad M = \frac{p+1-2a}{2}, \quad m_1 = \frac{n+1-2b}{2}, \quad m_2 = \frac{3-2c}{2}$$

Interactions with the Higgs Boson

- The notation can be simplified by putting the two fermions in one representation

$$\hat{\psi} = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \xrightarrow[\text{diag.}]{\text{mass}} \tilde{\psi} \qquad \text{with} \quad \begin{cases} P_L \hat{\psi} = R_L P_L \tilde{\psi} \\ P_R \hat{\psi} = R_R P_R \tilde{\psi} \end{cases}$$

  and define

due to Higgs doublet

$$d^{pn}_{ab} = \begin{cases} \hat{d}^{pn}_{a(b-p)2}, & \text{if } a \in [1,p] \text{ and } b \in [p+1, p+n] \\ 0, & \text{otherwise.} \end{cases}$$

- The interactions with the Higgs boson are then given by

$$\mathcal{L}_m \supset -\sum_{a,b} \Omega_{ab} h \overline{\tilde{\psi}^a} P_L \tilde{\psi}^b + \text{ H.c.}$$

  where the couplings

neither Hermitian nor diagonal

$$\Omega = \frac{A_L}{\sqrt{2}} R_R^\dagger d^{pn} R_L + \frac{A_R^*}{\sqrt{2}} R_R^\dagger d^{pnT} R_L$$

Gauge Interactions

- The interactions of the A/A' with $\tilde{\psi}$ are controlled by

$$\mathcal{L}_g \supset -eA_\mu \overline{\tilde{\psi}} \gamma^\mu \tilde{Q} \tilde{\psi} - Q' \underbrace{e'}_{U(1)' \text{ gauge coupling}} A'_\mu \overline{\tilde{\psi}} \gamma^\mu \tilde{\psi}$$

where $\tilde{Q}$ is the diagonal charge matrix as QED is a vector-like interaction.

- The interaction between the Z boson and $\tilde{\psi}$ is controlled by

$$\mathcal{L}_g \supset -\sqrt{g^2 + g'^2} Z_\mu \overline{\tilde{\psi}} \gamma^\mu \left(B_L P_L + B_R P_R \right) \tilde{\psi}$$

Hermitian but non-diagonal

- The interaction between the W boson and $\tilde{\psi}$ is controlled by

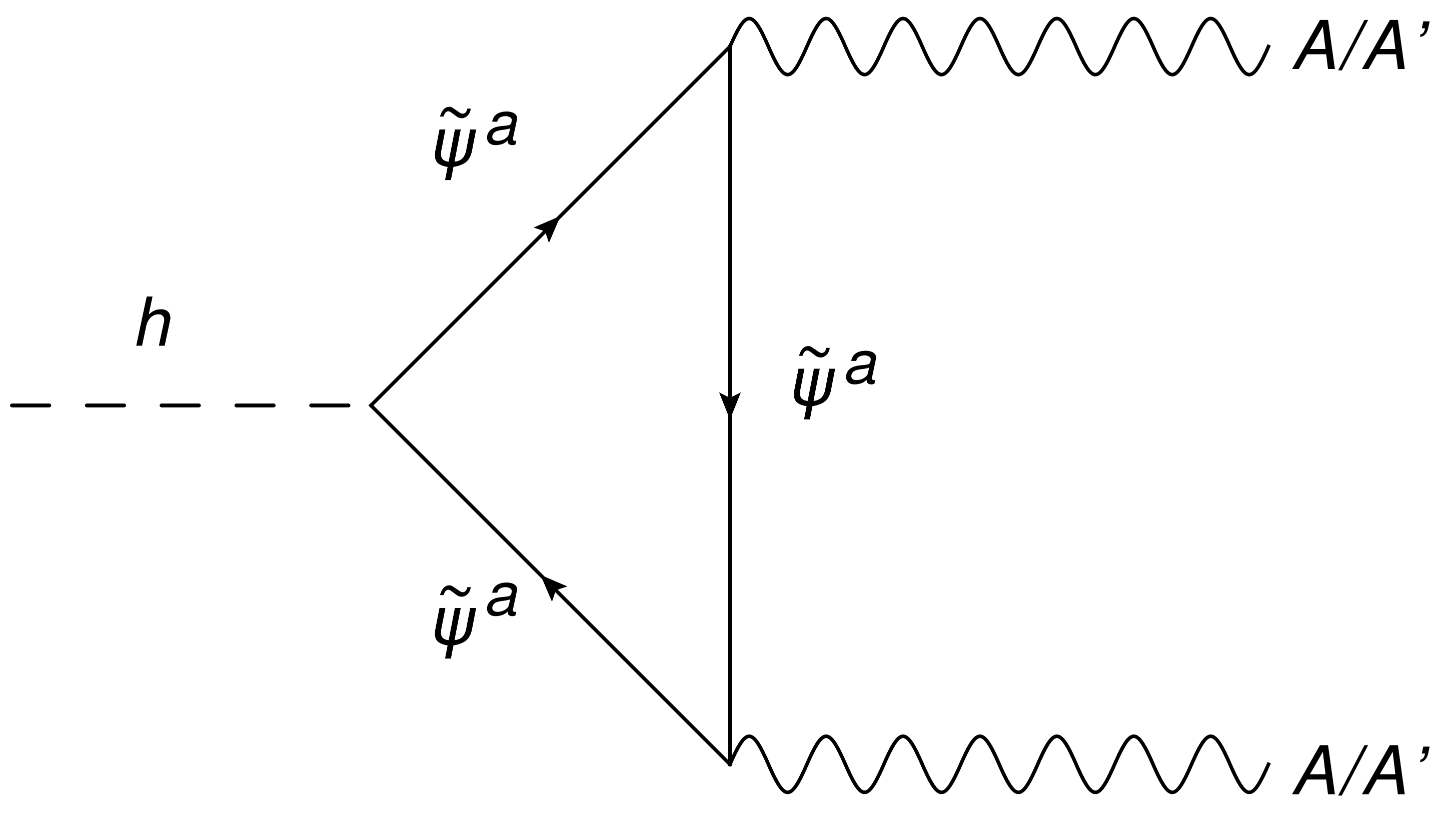
$$\mathcal{L}_g \supset -\frac{g}{\sqrt{2}} \overline{\tilde{\psi}} \gamma^\mu \left(\hat{A}_L P_L W^+_\mu + \hat{A}_R P_R W^+_\mu \right) \tilde{\psi} + \text{ H.c.}$$

Hermitian but non-diagonal

Detailed expressions of $B_{L,R}$ and $\hat{A}_{L,R}$ are given in the paper.

Higgs Decays

- The interactions of $\tilde{\psi}$ lead to contributions not only to the amplitude of $h \to AA'$, but also to those of the experimentally constrained AA and $A'A'$ (invisible) decays.



- Irrespective of the mediators, gauge invariance forces the amplitudes to take the forms

CP-conserving

CP-violating; no such terms in scalar cases

$$M^{h\to AA} = S^{h\to AA}\left(p_1\cdot p_2 g_{\mu\nu} - p_{1\mu}p_{2\nu}\right)\epsilon^{\nu}_{p_1}\epsilon^{\mu}_{p_2} + i\tilde{S}^{h\to AA}\epsilon_{\mu\nu\alpha\beta}p_1^{\alpha}p_2^{\beta}\epsilon^{\nu}_{p_1}\epsilon^{\mu}_{p_2}$$

$$M^{h\to AA'} = S^{h\to AA'}\left(p_1\cdot p_2 g_{\mu\nu} - p_{1\mu}p_{2\nu}\right)\epsilon^{\nu}_{p_1}\epsilon^{\mu}_{p_2} + i\tilde{S}^{h\to AA'}\epsilon_{\mu\nu\alpha\beta}p_1^{\alpha}p_2^{\beta}\epsilon^{\nu}_{p_1}\epsilon^{\mu}_{p_2}$$

$$M^{h\to A'A'} = S^{h\to A'A'}\left(p_1\cdot p_2 g_{\mu\nu} - p_{1\mu}p_{2\nu}\right)\epsilon^{\nu}_{p_1}\epsilon^{\mu}_{p_2} + i\tilde{S}^{h\to A'A'}\epsilon_{\mu\nu\alpha\beta}p_1^{\alpha}p_2^{\beta}\epsilon^{\nu}_{p_1}\epsilon^{\mu}_{p_2}$$

momenta of outgoing gauge bosons

$$S^{h\to AA}_{\rm SM} \approx 3.3\times 10^{-5}\ \text{GeV}^{-1}$$

$$\tilde{S}^{h\to AA}_{\rm SM} \approx 0\ \text{GeV}^{-1}$$

- Need to work out S and $\tilde{S}$ model by model.

Higgs Decays

- For the fermion mediators, the coefficients are given at one loop by

$$S^{h\to AA} = e^2 \sum_a \mathrm{Re}\left(\Omega_{aa}\right) \tilde{Q}^2_{aa} S_a + S^{h\to AA}_{\mathrm{SM}} \qquad \tilde{S}^{h\to AA} = e^2 \sum_a \mathrm{Im}\left(\Omega_{aa}\right) \tilde{Q}^2_{aa} \tilde{S}_a + \tilde{S}^{h\to AA}_{\mathrm{SM}}$$

$$S^{h\to AA'} = ee' \sum_a \mathrm{Re}\left(\Omega_{aa}\right) \tilde{Q}_{aa} Q' S_a \qquad \tilde{S}^{h\to AA'} = ee' \sum_a \mathrm{Im}\left(\Omega_{aa}\right) \tilde{Q}_{aa} Q' \tilde{S}_a$$

$$S^{h\to A'A'} = e'^2 \sum_a \mathrm{Re}\left(\Omega_{aa}\right) Q'^2 S_a \qquad \tilde{S}^{h\to A'A'} = e'^2 \sum_a \mathrm{Im}\left(\Omega_{aa}\right) Q'^2 \tilde{S}_a$$

with the loop factors

$$S_a = \frac{-m_a}{2\pi^2 m_h^2}\left[2 + \left(4m_a^2 - m_h^2\right) C_0\left(0, 0, m_h^2; m_a, m_a, m_a\right)\right]$$

mediator mass

$$\tilde{S}_a = -i\frac{m_a}{2\pi^2} C_0\left(0, 0, m_h^2; m_a, m_a, m_a\right)$$

scalar three-point Passarino-Veltman function

Higgs Decays

- The partial decay widths are given by

$$\Gamma^{h\to AA} = \frac{\left|S^{h\to AA}\right|^2 + \left|\tilde{S}^{h\to AA}\right|^2}{64\pi} m_h^3$$

— symmetry factor included

$$\Gamma^{h\to AA'} = \frac{\left|S^{h\to AA'}\right|^2 + \left|\tilde{S}^{h\to AA'}\right|^2}{32\pi} m_h^3$$

$$\Gamma^{h\to A'A'} = \frac{\left|S^{h\to A'A'}\right|^2 + \left|\tilde{S}^{h\to A'A'}\right|^2}{64\pi} m_h^3$$

— symmetry factor included

which are seen to be highly correlated.

sets by the only mass scale here

- The Higgs signal strengths (for AA and invisible modes) will therefore impose strong constraints on $\mathrm{BR}(h \to AA')$.

Remarks

- As shown in the expression:

$$S^{h\to AA} = e^2 \sum_a \mathrm{Re}\,(\Omega_{aa})\,\tilde{Q}_{aa}^2 S_a + S_{\mathrm{SM}}^{h\to AA}$$

  there are generally interference terms between the NP and SM contributions that may contradict the measured $\mathrm{BR}(h \to AA)$.

- To avoid this undesirable additional contribution and noting that $S_{\mathrm{SM}}^{h\to AA}$ is essentially purely real, the kinetic function S_a had better be purely imaginary.

- But this is impossible for fermions because S_a must be purely real, as bounds from the Large Electron-Positron collider (LEP) prevent charged mediators from being sufficiently light to be able to go on shell in the triangle diagram.

Remarks

- Another way to avoid interference terms is for the mediators to contribute to $\tilde{S}^{h\to AA}$ only.
- This can indeed be done for fermion mediators and the signal strength constraints can therefore mostly be evaded.
- However, a large $\mathrm{BR}(h \to AA')$ will in this case lead to a large EDM for the electron.
- The limits on the EDM will force the complex phase to be small and will close this loophole.

- Therefore, both kinetic functions S_a and $\tilde{S}_a$ have to be negligibly small.
  ➠ suppressing $\mathrm{BR}(h \to AA')$

Remarks

- It is possible to perform a naive estimate of the upper limit on $\mathrm{BR}(h \to AA')$ allowed by the Higgs signal strengths.
- Suppose that a single mediator dominates the amplitude.
- Assume as justified above that $\mathrm{Im}(\Omega_{ii}) = \mathrm{Im}(S_a) = 0$.
- Define $\Delta\mathrm{BR}(h \to AA)$ to be the deviation of $\mathrm{BR}(h \to AA)$ from its SM value and assume that it is small. Then, the following approximate relation holds:

$$\mathrm{BR}\,(h \to AA') \approx \sqrt{\underbrace{\mathrm{BR}\,(h \to A'A')}_{\leq 10\,\%}\,\underbrace{\mathrm{BR}(h \to AA)}_{\simeq 0.23\,\%}} \times \underbrace{\left|\frac{\Delta\mathrm{BR}(h \to AA)}{\mathrm{BR}(h \to AA)}\right|}_{\simeq \mathcal{O}(25\%)} \lesssim 0.4\%$$

Constraints to Impose

- We will impose the following constraints on the models:
    - Higgs signal strengths
    - electric dipole moment of the electron (eEDM) — for the fermion case only
    - electroweak oblique parameters
    - perturbative unitarity
    - perturbativity of $U(1)'$ couplings

χ^2 Fit to Higgs Signal Strengths

- We calculate the κ's for each of the models, e.g.,

$$\kappa_{AA}^2 = \frac{|S^{h\to AA}|^2 + |\tilde{S}^{h\to AA}|^2}{|S_{\rm SM}^{h\to AA}|^2 + |\tilde{S}_{\rm SM}^{h\to AA}|^2},$$

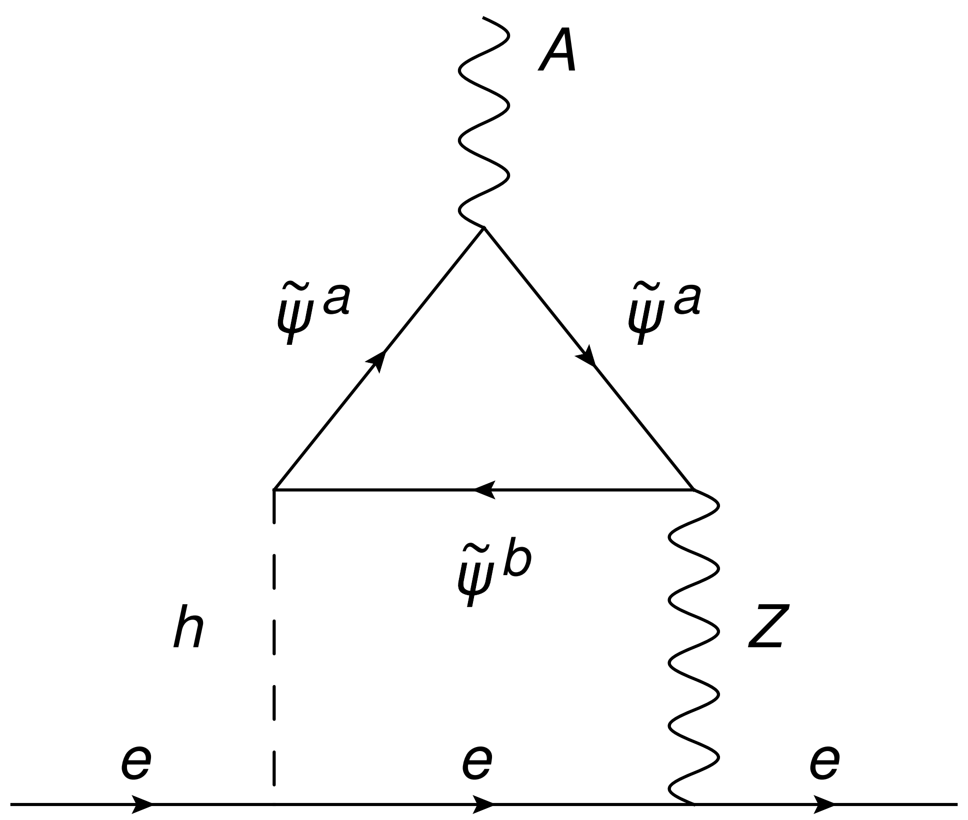
  and perform a χ^2 fit to the 13-TeV data provided ATLAS with 139 fb^{-1} of integrated luminosity and CMS with 137 fb^{-1} of integrated luminosity.

CMS 2020
ATLAS 2021, 2023

- As we will be interested in two-dimensional scans, a point of parameter space will be considered excluded at 95% CL if its χ^2 satisfies $\chi^2 - \chi^2_{\rm min} > 5.99$, where $\chi^2_{\rm min}$ is for the best fit of the model.

Electron EDM

- The scenario of having purely imaginary Ω_{aa} couplings is constrained by the eEDM data because such models can contribute to the Barr-Zee diagrams.



  - hA diagrams dominate when $\mathrm{BR}(h \to AA')$ is close to its maximally allowed value, and their contribution $\propto \mathrm{Im}(\Omega_{aa})$
  - forces Ω_{aa} to be purely real or simply tiny (virtually no CPV)
- The upper limit on the electron EDM is $|d_e| < 4.1 \times 10^{-30}\ e \cdot \mathrm{cm}$ at 90% CL.

Roussy et al 2022

Electroweak Oblique Parameters

- A sizable $\mathrm{BR}(h \to AA')$ requires some of the Yukawa couplings $A_{L,R}$ to be large.
- These couplings, however, have the side effect of causing mixing between fields that are part of different representations of the electroweak gauge groups.
  ➠ generating large contributions to the oblique parameters Peskin, Takeuchi 1990
- Currently, the S and T parameters are measured to be

$$S = 0.00 \pm 0.07, \quad T = 0.05 \pm 0.06$$

PDG 2020

  with a correlation of 0.92.
- We keep points with χ^2 differing by less than 5.99 from the best fit, which corresponds to 95% CL limits.

Perturbative Unitarity

- The Yukawa couplings $A_{L,R}$ are also bounded by unitarity.
- Consider a given scattering between mediators via Higgs exchange and its amplitude $\mathscr{M}$, which can be expanded in partial waves as

$$\mathcal{M} = 16\pi \sum_{\ell} (2\ell + 1) a_\ell P_\ell(\cos\theta)$$

- In the high energy limit, we can work directly with $\psi_{1,2}$ (the states before mass diagonalization) and compute the S-wave a_0 factor of every possible scattering $\overline{\psi}_1^a \psi_2^b \to \overline{\psi}_1^c \psi_2^d$ for every possible helicity combination.
- Unitarity imposes

$$\max\left(\left|\mathrm{Re}\left(\underbrace{a_0^{\mathrm{eig}}}_{\text{eigenvalue}}\right)\right|\right) < \frac{1}{2} \;\Leftrightarrow\; |A_R|^2 + |A_L|^2 < \frac{32\pi}{\underbrace{p}_{SU(2)\text{ dimension}}}$$

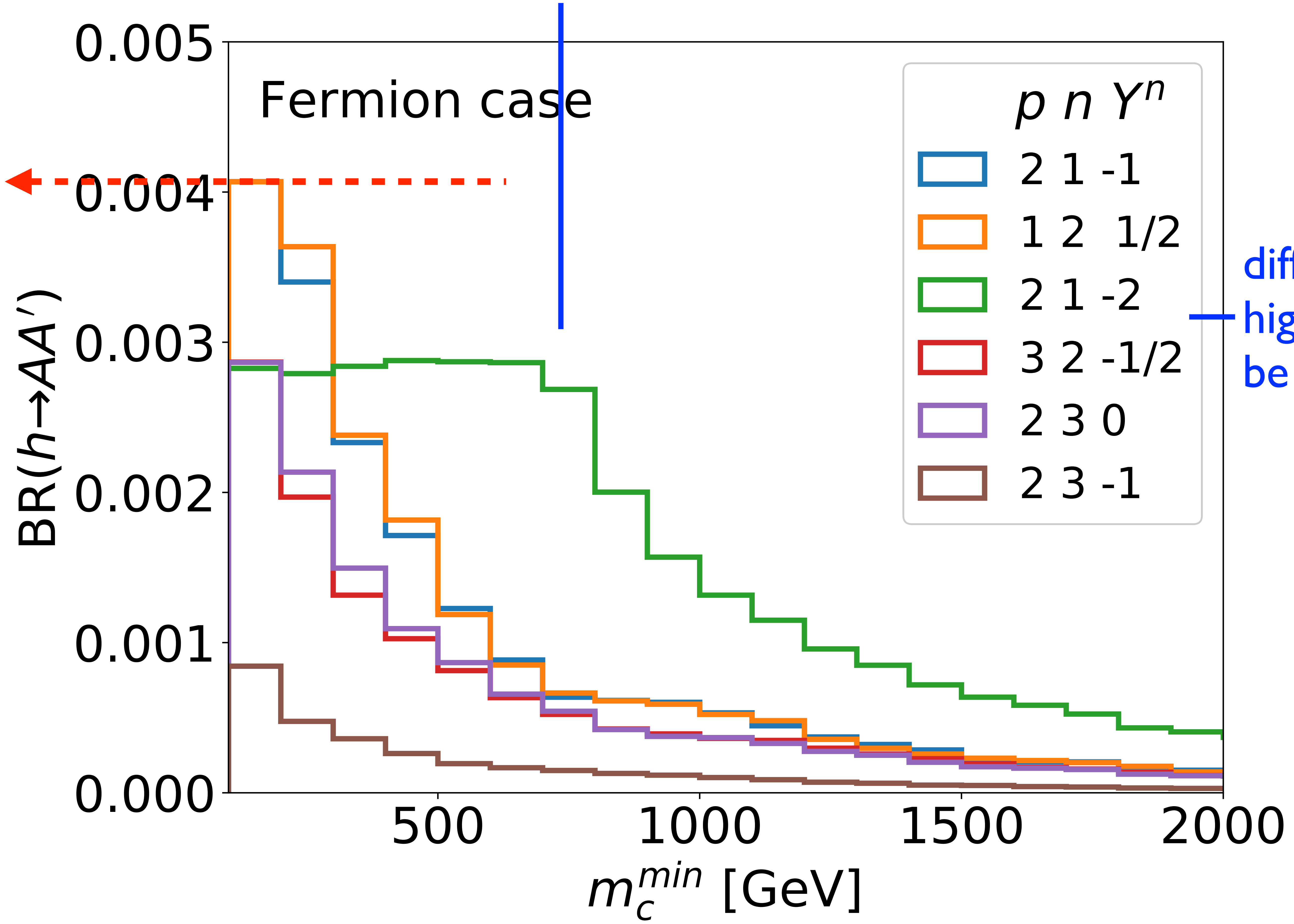
Parameter Space Exploration

- Consider multiple benchmark models for each class.
  ➠ mediators of larger representations are generally very constrained
- Scan the entire parameter space with the Markov chain using the Metropolis-Hasting algorithm.
- Impose $|Q'e'| < \sqrt{4\pi}$ as a perturbativity bound.
- To maximize the number of points near the limits and thus reduce the necessary number of simulations, assume a prior $\propto \mathrm{BR}(h \to AA')^2$.
- We have verified that the results are independent of the sampling algorithm and prior.

Results of the Fermion Case

often plateau first, followed by sudden drop above a certain threshold in m_c^{min}; due to more powerful constraints from the oblique parameters and/or unitarity

an upper bound of about 0.4%, appearing in the low-mass regime; coming from the Higgs signal strengths and consistent with the approximate estimate



different representations; higher representations seen to be even more severely bounded

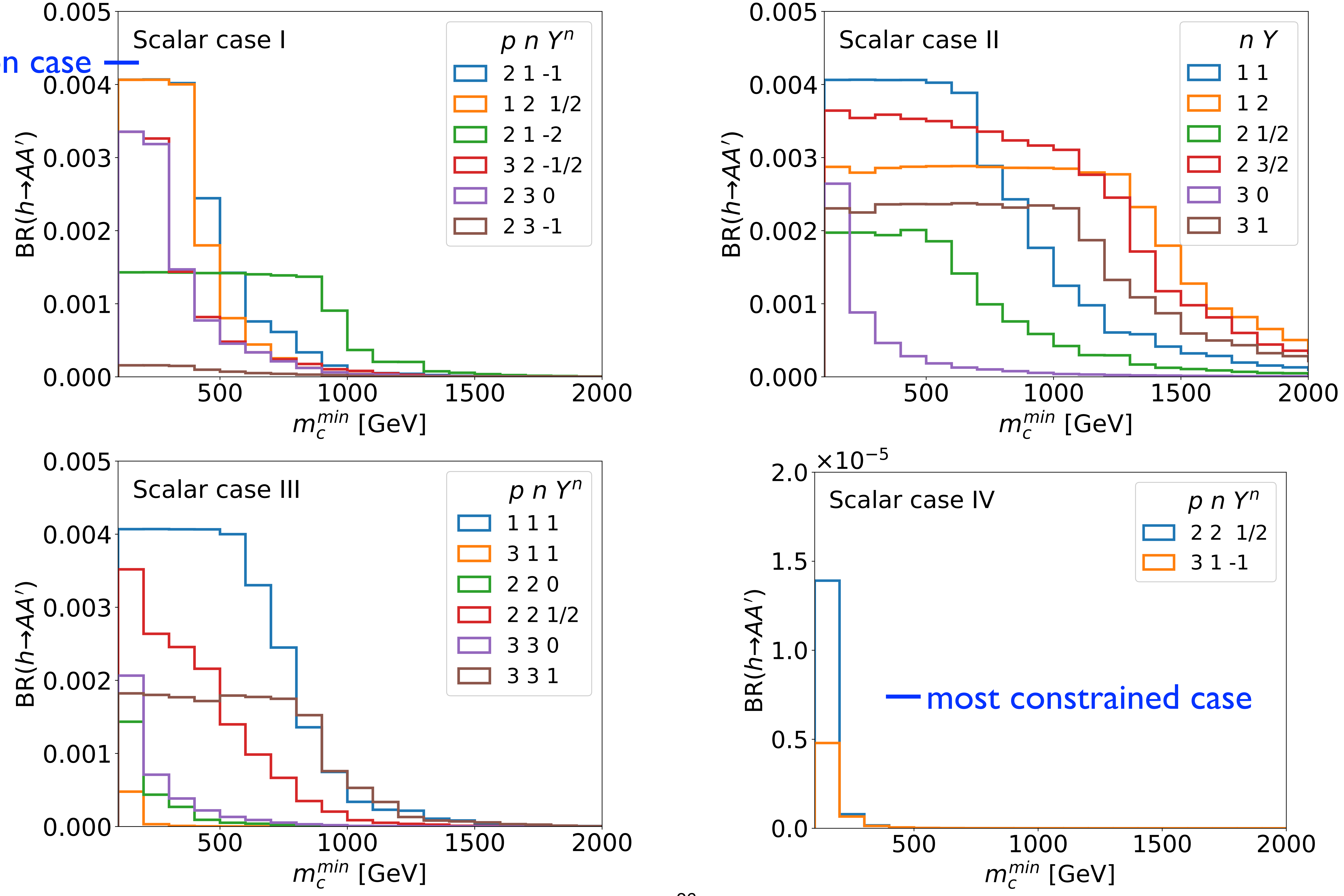
mass of the lightest electrically charged mediator

Remarks

- There should be a lower limit on the mass of the charged mediators coming from collider searches.
  ➠ tighter bound on $\mathrm{BR}(h \to AA')$ if this lower mass limit is higher than the threshold in m_c^{min}
- In principle, the mediators could decay to exotic channels that have not been probed yet.
  ➠ technically impossible to determine a model-independent mass bound
- Given the fact that it would be very difficult for a charged particle of less than a few hundred GeV not to have been observed at the LHC by now, obtaining a large $\mathrm{BR}(h \to AA')$ would require a charged light particle that has avoided detection in a contrived way.

Results of the Scalar Cases

similar to fermion case



Summary

- We have investigated experimental and theoretical constraints on $\mathrm{BR}(h \to AA')$.
- $\mathrm{BR}(h \to AA') \lesssim 0.4\,\%$ or stronger, across a wide class of models.
- Our bounds are far stronger constraints than previous phenomenology papers (5%) and experimental searches (1.8%).
- It would be very challenging to probe this channel at the LHC with its limited sensitivity.
- The bounds are unavoidably model-dependent, but quite general for generic models.
- Should experiments observe this channel, it would point to some very contrived new physics models.

Thank You!