Mediator Decay through Mixing with Degenerate Spectrum

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(arXiv:2404.06793)

- ✓ Light mediator is often predicted in the dark sector scenario.
- ✓ The mediator weakly interacts with the SM particles in general. A small coupling controls the strength of such an interaction.
- ✓ However, the interaction could be enhanced if the mediator degenerates with an SM state with the same quantum number.
- ✓ We discuss how the influence of the degeneracy is correctly described, focusing on the lifetime of the mediator particle.

Dark sector scenario

A scenario addressing big questions in PP (DM, ν mass, BAU, etc.)

< EW scale

Standard Model — Weak Connection — Dark sector

- ✓ Via higher-dim. operator (Or very heavy particles).
- ✓ Hidden valley scenario.
- ✓ Via light mediator particle

Origin of
- ✓ the dark matter,
- ✓ the neutrino masses/mixings,
- ✓ the baryon asymmetry of U., etc.

Ex.) Fermionic singlet (thermal) dark matter in the dark sector

Suppose that the dark matter is stabilized by the Z_2 symmetry, and interacts with the SM particles via renormalizable interactions,

Any renormalizable interaction between DM and SM particles can not be written in an SM+DM system due to the Z_2 and SM sym.

A mediator particle must be introduced in theory, and its mass must be light enough to explain the dark matter abundance observed today.

Mediator particle

Various mediator particles are now being considered in the literature.

To guarantee weak interactions among the light mediator particle & SM particles, the mediator should be singlet under the SM gauge group.

The following three mediator particles are being intensively studied, as the simplest mediator candidates with the spin of 0, ½, and 1.

Dark Higgs Φ

✓ Spin-0 mediator

✓ Interaction(s)

$\Phi|H|^2$, $\Phi^2|H|^2$

H: Higgs doublet

It causes the mixing between ϕ and H, so the mediator tends to interact with heavy SM particles.

Dark photon V

✓ Spin-1 mediator

✓ Interaction

e.g., $V_{\mu\nu} B^{\mu\nu}$

B : Hyper-charge gauge boson

It causes the mixing between V & γ, so it couples to charged SM particles.

Sterile neutrino N

✓ Spin-½ mediator

✓ Interaction

LHN + h.c.

L: Lepton doublet

It causes the mixing between N and SM neutrinos ν, so N interacts mainly with SM leptons.

Implications to collider physics & cosmology

∵ *Light mediator particle is light and weakly interacting with the SM!*

○ Typical production modes

Direct prod., e.g., ee → Med + X.

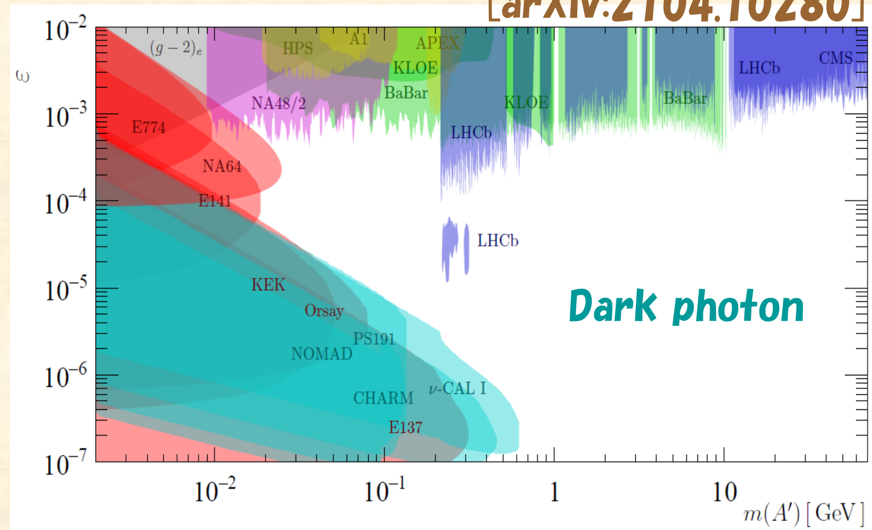
Boson decay, e.g., B → Med + X.

○ Typical decay modes

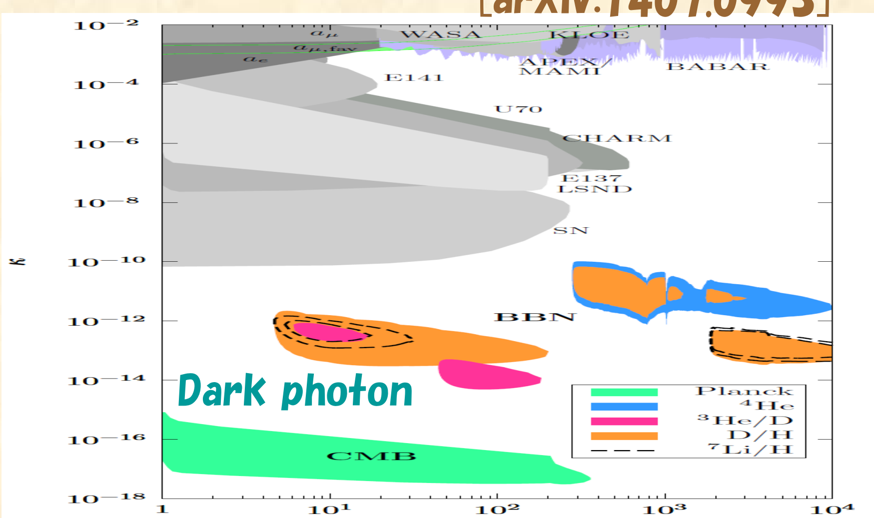
Decays into an SM particle pair, such as Med → $\mu\mu$, KK, BB, etc.

It could be a long-lived particle at various collider experiments!

[arXiv:2104.10280]



[arXiv:1407.0993]



It could affect the evolution of the universe as a long-lived light relic.

✓ Spoiling the successful BBN.

✓ Modifying CMB via its decay.

✓ Pulling energy out from stars.

✓ Modifying CMB via V ←→ γ.

✓ May play a role of dark matter.

Vector mediator as an example

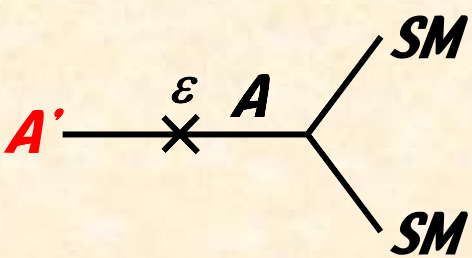
*Let us consider such a case using **the dark photon mediator** scenario!*

✓ *Starting Lagrangian is*

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}\overline{m}^2_{A'}A'^2_\mu + \frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$$

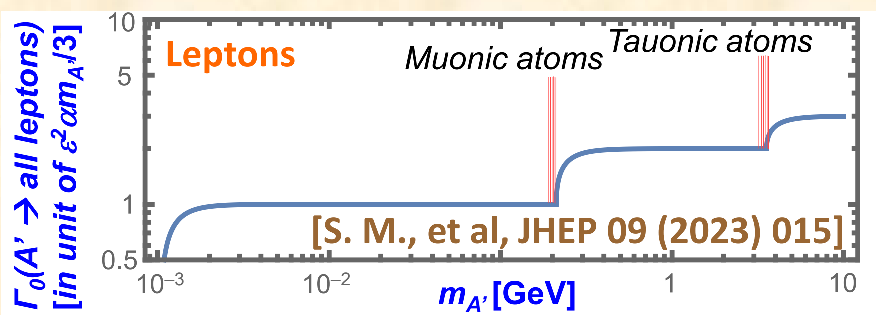
The mediator mass term is assumed to be from a Higgs mechanism.
The dark photon interacts with the SM particles through the EM currents when its mass is smaller enough than the EW scale.

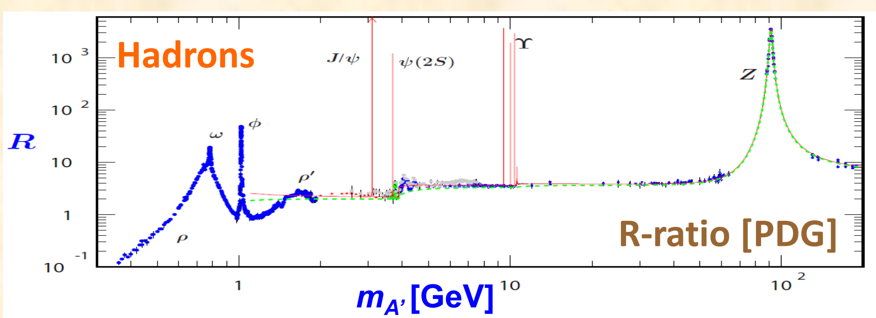
✓ *Calculating its **width** (lifetime) @ LO ($\varepsilon \ll 1$)*



$$\Gamma_0(A' \to \ell_i^- \ell_i^+) \simeq \epsilon^2 \frac{\alpha m_{A'}}{3}\left(1 + 2\frac{m^2_{\ell_i}}{m^2_{A'}}\right)\sqrt{1 - \frac{4m^2_{\ell_i}}{m^2_{A'}}}$$

$$\Gamma_0(A' \to \text{all hadrons}) \simeq \epsilon^2 \frac{\alpha m_{A'}}{3}\left(1 + 2\frac{m^2_{\mu}}{m^2_{A'}}\right)\sqrt{1 - \frac{4m^2_{\mu}}{m^2_{A'}}}\,R$$



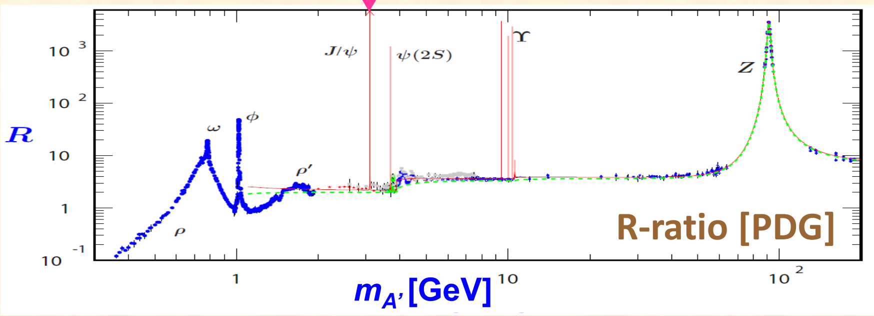


Dark photon degenerated with an SM state

Interaction between the mediator and the SM particles is enhanced when it degenerates with an SM state (V) with the same quantum #.

✓ Is it possible to very significantly enhance the interaction?

E.g., at here.



The mixing term ($\propto \varepsilon$) contributes to an off-diagonal element of the mass matrix between A' and V.

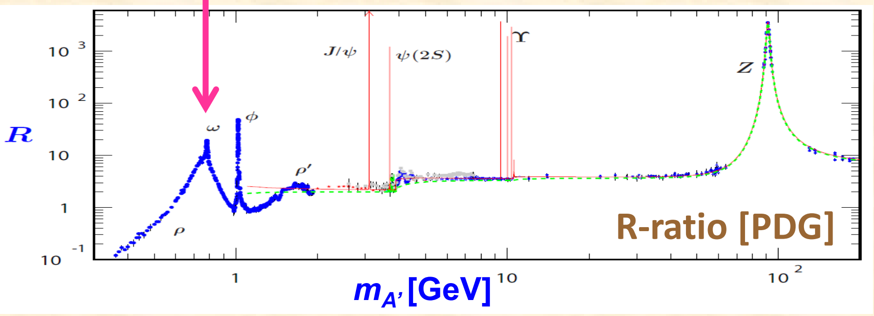
↓ Diagonalization

$$\tilde{A}' = A' \cos\theta + V \sin\theta$$

The decay width of $\tilde{A}'$ is, at most, that of the degenerate particle V.

✓ Is the interaction very significantly enhanced when the mediator degenerates with an SM state that has a huge decay width?

E.g., at here.



As an SM state with a huge decay width means a broad resonance, namely far from a quasi-particle, the previous formula should work…

Let us consider it more carefully.

Lagrangian for A, A' and V

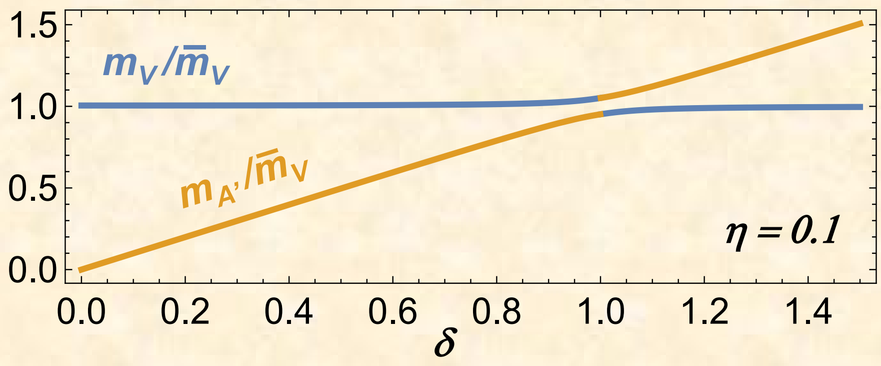
$$\mathcal{L} = -\frac{1}{4}\bar{F}_{\mu\nu}\bar{F}^{\mu\nu} - \frac{1}{4}\bar{F}'_{\mu\nu}\bar{F}'^{\mu\nu} - \frac{1}{4}\bar{V}_{\mu\nu}\bar{V}^{\mu\nu} + \frac{\epsilon}{2}\bar{F}_{\mu\nu}\bar{F}'^{\mu\nu} + \frac{\epsilon_V}{2}\bar{F}_{\mu\nu}\bar{V}^{\mu\nu} + \frac{\epsilon'_V}{2}\bar{F}'_{\mu\nu}\bar{V}^{\mu\nu}$$
$$+ \frac{1}{2}\bar{m}^2_{A'}\bar{A}'_\mu\bar{A}'^\mu + \frac{1}{2}\bar{m}^2_V\bar{V}_\mu\bar{V}^\mu + e\bar{A}_\mu J^\mu_A + g_V\bar{V}_\mu J^\mu_V + g_{A'}\bar{A}'_\mu J^\mu_{A'} + \cdots$$

V = Z, ρ, Ps, etc.

Diagonalization

$$\begin{pmatrix}\bar{A}'_\mu\\ \bar{V}_\mu\\ \bar{A}_\mu\end{pmatrix} = C_{\rm kin}\begin{pmatrix}\tilde{A}'_\mu\\ \tilde{V}_\mu\\ \tilde{A}_\mu\end{pmatrix} = C_{\rm kin}\begin{pmatrix}\cos\theta & \sin\theta & 0\\ -\sin\theta & \cos\theta & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}A'_\mu\\ V_\mu\\ A_\mu\end{pmatrix} \equiv C\begin{pmatrix}A'_\mu\\ V_\mu\\ A_\mu\end{pmatrix}$$

$$\mathcal{L} \supset \frac{1}{2}\bar{m}^2_V\begin{pmatrix}\tilde{A}'_\mu & \tilde{V}_\mu\end{pmatrix}\begin{pmatrix}\eta^2+\delta^2 & -\eta\\ -\eta & 1\end{pmatrix}\begin{pmatrix}\tilde{A}'_\mu\\ \tilde{V}'_\mu\end{pmatrix} = \frac{1}{2}\begin{pmatrix}A'_\mu & V_\mu\end{pmatrix}\begin{pmatrix}m^2_{A'} & 0\\ 0 & m^2_V\end{pmatrix}\begin{pmatrix}A'_\mu\\ V_\mu\end{pmatrix}$$



$\eta = \eta(\varepsilon, \varepsilon_V, \varepsilon'_V)$, $\delta \propto \bar{m}_{A'}^2/\bar{m}_V^2$

← *The vector particles A' and V never degenerate in mass in a complete way. (The so-called avoided level crossing.)*

Discontinuity exists at δ close to 1.

2 familiar ways to calculate the A's lifetime

Suppose the following interactions: $\mathcal{L}_{\rm int} = g_V \overline{V}_\mu \bar{f}\gamma^\mu f + eQ_f \overline{A}_\mu \bar{f}\gamma^\mu f$

✓ "Classical" method:

Diagonalizing kinetic and mass terms and calculating the width.

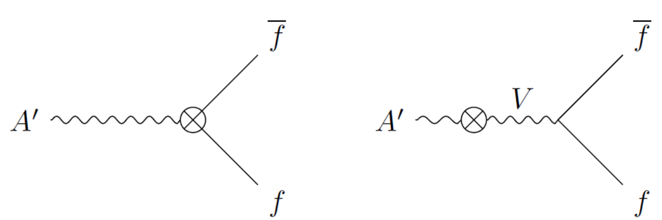
$$\mathcal{L}_{\rm int} = \left(C_{\overline{V}A'}\, g_V + C_{\overline{A}A'}\, eQ_f\right) A'_\mu \bar{f}\gamma^\mu f + \left(C_{\overline{V}V}\, g_V + C_{\overline{A}V}\, eQ_f\right) V_\mu \bar{f}\gamma^\mu f + \cdots$$

$$\Gamma_{\rm CL}(A' \to f\bar{f}) = \frac{m_{A'}}{16\pi}\frac{4}{3}\left(C_{\overline{V}A'}\, g_V + C_{\overline{A}A'}\, eQ_f\right)^2 \xrightarrow[\text{w/ fixed } \varepsilon \ll 1]{\delta \to 1} \frac{m_{A'}}{16\pi}\frac{2}{3} g_V^2 \simeq \Gamma_{\rm CL}(V \to f\bar{f})$$

✓ "ε-insertion" method

Diagonalizing kinetic terms and calculating the width with a perturbative ε.

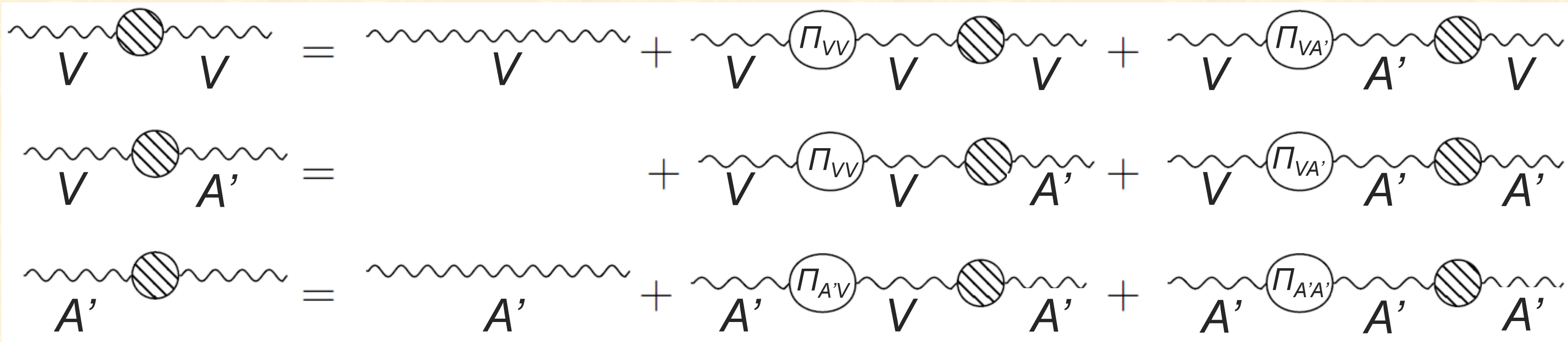
$$\Gamma_{\varepsilon I}(A' \to f\bar{f}) = \frac{M_{\tilde{A}'}}{16\pi^2}\frac{4}{3}\left| \bar{g}_f^{\tilde{A}'} + \bar{g}_f^{\tilde{V}} \frac{-\overline{m}_V^2 \eta}{M_{\tilde{A}'}^2 - \overline{m}_V^2 + i\overline{m}_V \Gamma_{\tilde{V}}} \right|^2 \quad \left\{ \begin{aligned} \bar{g}_f^{\tilde{V}} &\equiv (C_{\rm kin})_{\overline{V}\tilde{V}}\, g_V + (C_{\rm kin})_{\overline{A}\tilde{V}}\, eQ_f \\ \bar{g}_f^{\tilde{A}'} &\equiv (C_{\rm kin})_{\overline{V}\tilde{A}'}\, g_V + (C_{\rm kin})_{\overline{A}\tilde{A}'}\, eQ_f \\ M_{\tilde{A}'}^2 &= \overline{m}_V^2(\delta^2 + \eta^2), \\ \overline{\Gamma}_V &= \frac{\overline{m}_V}{16\pi}\frac{4}{3} g_V^2 . \end{aligned} \right.$$



$$\xrightarrow[\text{w/ fixed } \varepsilon \ll 1]{\delta \to 1} \Gamma_{\varepsilon I}(A' \to f\bar{f}) \propto \varepsilon^2$$

Proper definition of the masses & widths

The masses and widths are defined by poles of the $f\bar{f} \to f\bar{f}$ process.



Dyson equations

$$\Pi^{IJ}_{\mu\nu}(p^2) = \left(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right)\Pi_{IJ}(p^2) + \frac{p_\mu p_\nu}{p^2}\Delta_{IJ}(p^2)$$

$$[s - m_V^2 - \Pi_{VV}(s)][s - m_{A'}^2 - \Pi_{A'A'}(s)] - [\Pi_{VA'}(s)]^2 = 0$$

When $m_f = 0$

$$\Pi_{IJ}(s) = s\,\Pi'_{IJ}(0)$$

@ 1-loop level

($\delta \to 1$ w/ fixed $\varepsilon \ll 1$)

$$\Pi'_{VV} \simeq \Pi'_{A'A'} \simeq -\Pi'_{VA'} = \mathcal{O}(\eta^0) \equiv \Pi' \simeq -i\,\overline{\Gamma}_V/\overline{m}_V$$

✓ **When** $|\eta| \gtrsim \overline{\Gamma}_V/\overline{m}_V$, **then** $s^{\pm}_{\rm pole} \simeq m_V^2\,(1 + \Pi')$

The poles degenerate w/ $O(\eta^0)$ imaginary parts ~ Classical method.

✓ **When** $|\eta| \lesssim \overline{\Gamma}_V/\overline{m}_V$, **then** $s^{\pm}_{\rm pole} \simeq m_V^2\,(1 + \Pi' \pm \Pi')$

One has $O(\eta^0)$, and another has $O(\eta^2)$ widths ~ ε-insertion" method.

Concrete examples

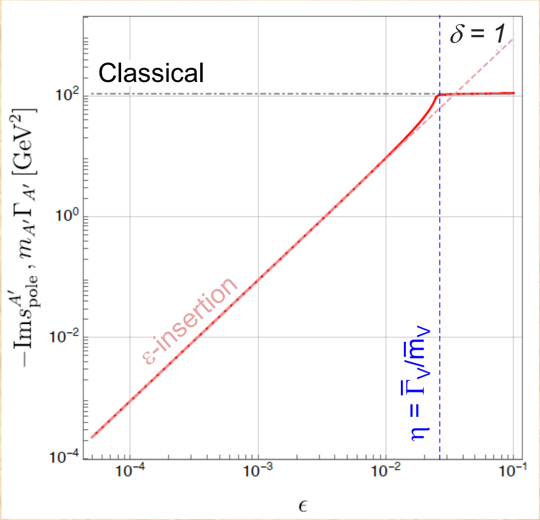
V = Z case

$\bar{m}_V$ = 91.2 GeV
$\bar{\Gamma}_V$ = 2.50 GeV

From SM theory,

$$\eta = \frac{\epsilon \tan\theta_W}{(1-\epsilon^2/\cos^2\theta_W)^{1/2}}$$

$$\delta = \frac{\overline{m}_{A'}/\overline{m}_V}{(1-\epsilon^2/\cos^2\theta_W)^{1/2}}$$



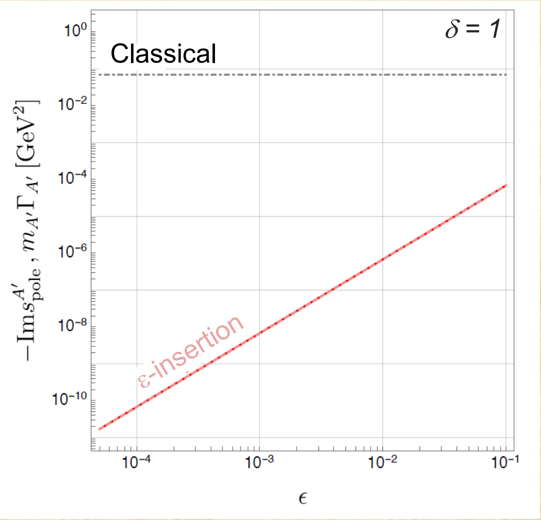
V = ρ case

$\bar{m}_V$ = 775 MeV
$\bar{\Gamma}_V$ = 147 MeV

From HLS theory,

$$\eta = \frac{\epsilon_{\mathrm{eff}}}{(1-\epsilon_{\mathrm{eff}}^2)^{1/2}} \qquad \delta = \frac{\overline{m}_{A'}/\overline{m}_V}{(1-\epsilon_{\mathrm{eff}}^2)^{1/2}}$$

$$\epsilon_{\mathrm{eff}} = \frac{\epsilon}{(1-\epsilon^2)^{1/2}}\frac{e/g}{(1-e^2/g^2)^{1/2}}$$



V = $(\mu^-\mu^+)$ case

$\bar{m}_V$ = 211 MeV
$\bar{\Gamma}_V$ = 366 μeV

From NRL theory,

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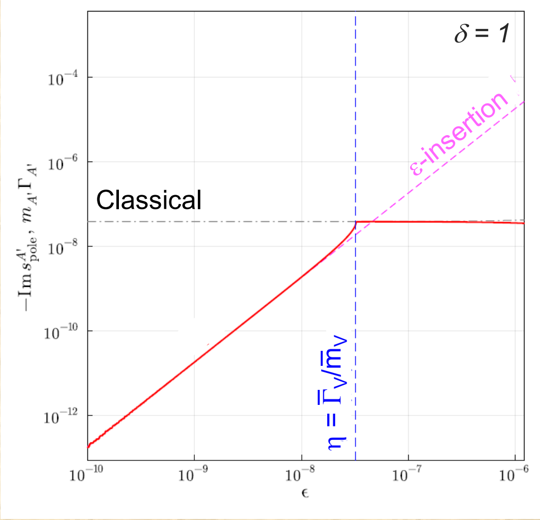
$$\epsilon_{\mathrm{eff}} = \frac{\epsilon}{(1-\epsilon^2)^{1/2}}\frac{\alpha^2/2}{(1-\alpha^4/4)^{1/2}}$$



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V = Z ca

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$$\eta = \frac{\epsilon \tan}{(1-\epsilon^2/\,\mathrm{co}}$$

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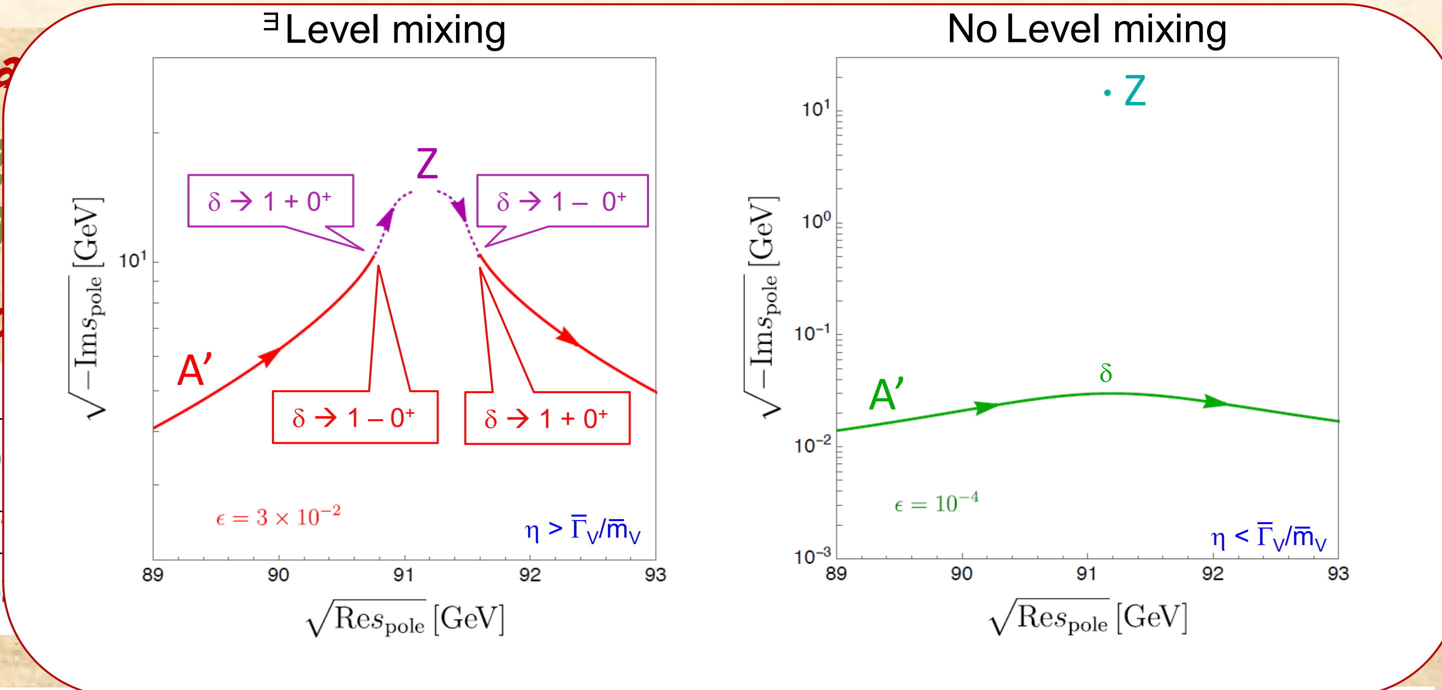

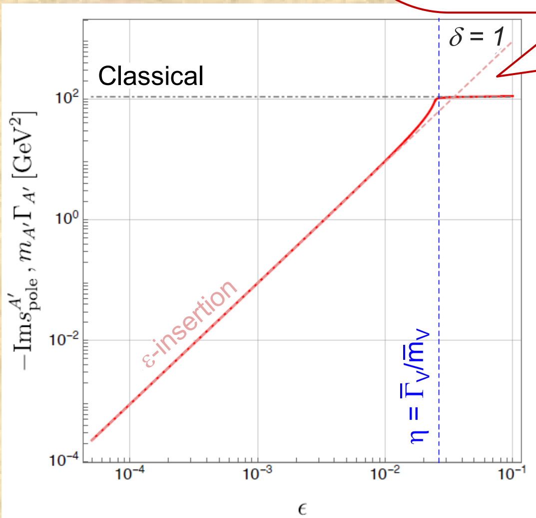

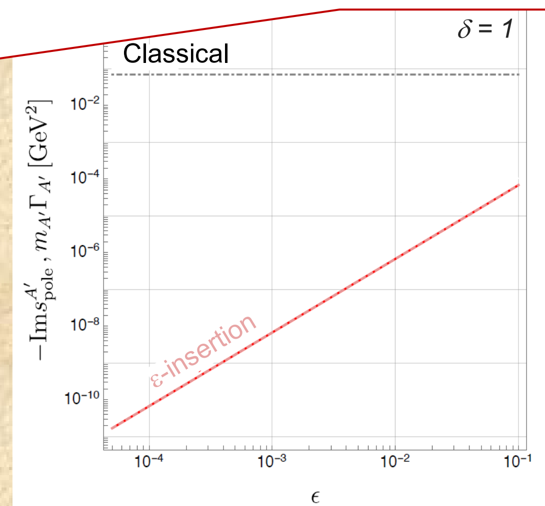

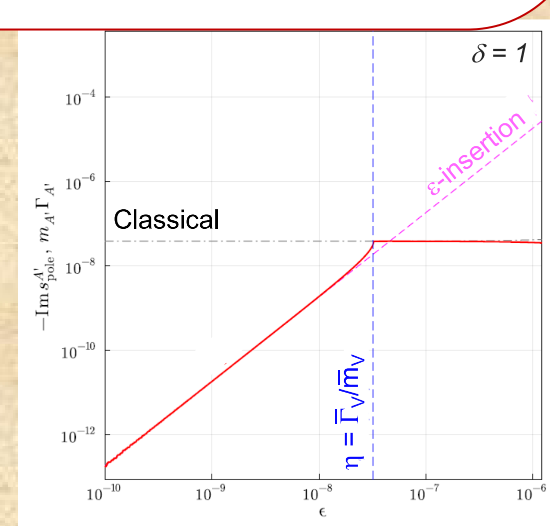

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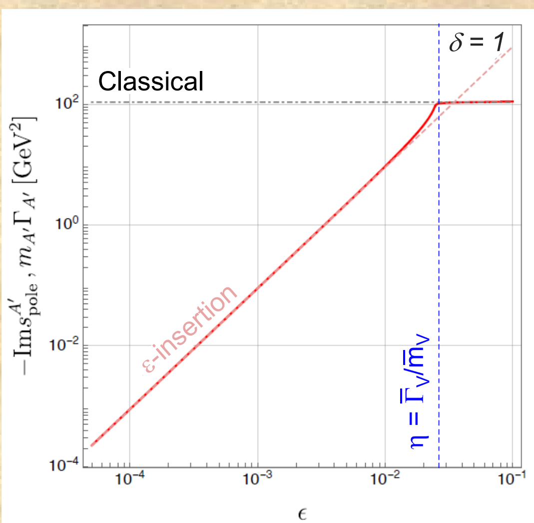

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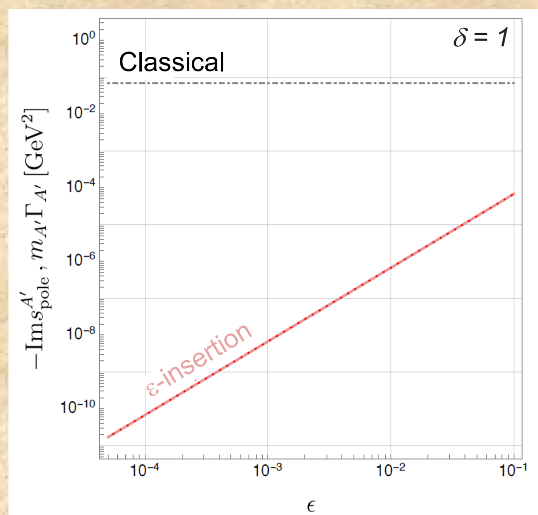

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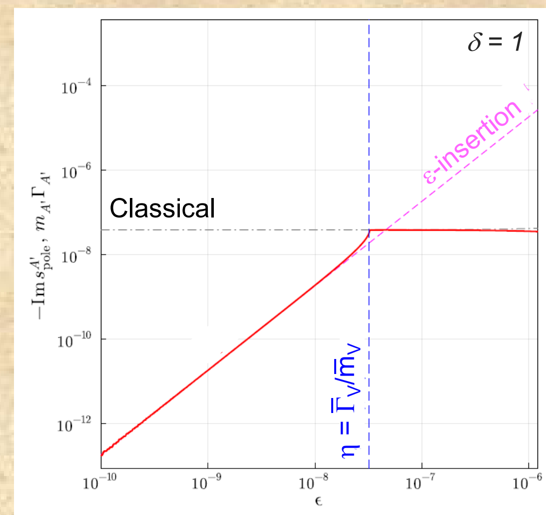

Summary

- ✓ We discussed how the decay width of the mediator particle (dark photon) should be computed when it degenerates with an SM state.
- ✓ When $\eta > \Gamma_V/m_V$, the level mixing exists, and the width is obtained by the "classical" method, with Γ_V and m_V being the mass and width the SM state originally had before interacting with the mediator.
- ✓ When $\eta < \Gamma_V/m_V$, no level mixing exists, and the width is calculated by the "ε-insertion" method, where ε is treated perturbatively.
- ✓ In other words, the width of the mediator is given by min$[\Gamma_{CL}, \Gamma_{\varepsilon I}]$.
- ✓ The method developed here is, of course, applied to other V cases.
- ✓ The method is also applied to another particle degenerating with the other particle, such as other mediators degenerating with an SM sate and right-handed neutrinos in the resonant leptogenesis.

Summary

Mesons	Mass (MeV)	Width (MeV)	Branching ratio to e^-e^+	Critical mixing $\epsilon_{\rm cr}$
$\rho\,(770)$	775.26	149.1	4.72×10^{-5}	9.53×10^{-1}
$\omega\,(782)$	782.66	8.68	7.38×10^{-5}	5.26×10^{-1}
$\phi\,(1020)$	1019.461	4.249	2.979×10^{-4}	1.81×10^{-1}
$J/\psi\,(1S)$	3090.9	9.26×10^{-2}	5.971×10^{-2}	1.10×10^{-3}
$\psi\,(2S)$	3686	2.94×10^{-1}	7.93×10^{-3}	4.95×10^{-3}
$\psi\,(3770)$	3773.7	27.2	9.6×10^{-6}	8.04×10^{-1}
$\psi\,(4040)$	4039	80	1.07×10^{-5}	9.05×10^{-1}
$\psi\,(4160)$	4191	70	6.9×10^{-6}	9.25×10^{-1}
$\Upsilon\,(1S)$	9460	5.4×10^{-2}	2.38×10^{-2}	7.64×10^{-4}
$\Upsilon\,(2S)$	10023	3.198×10^{-2}	1.91×10^{-2}	6.38×10^{-4}
$\Upsilon\,(3S)$	10355	2.032×10^{-2}	2.18×10^{-2}	4.68×10^{-4}
$\Upsilon\,(4S)$	10579.4	20.5	1.57×10^{-5}	4.81×10^{-1}
$\Upsilon\,(10860)$	10885.2	37	8.3×10^{-6}	7.67×10^{-1}
$\Upsilon\,(11020)$	11000	24	5.4×10^{-6}	7.04×10^{-1}

- ✓ *The method developed here is, of course, applied to other V cases.*
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