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 properly 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.

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.

→ Dark scalar, Dark photon, Neutral fermion mediators, etc.

Because the mediator particle is light and very weakly interacting, it has implications for collider physics (LLP) and cosmology (light relics).

A key physical observable for the implications is its width (lifetime)!

Dark photon (as an example)

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

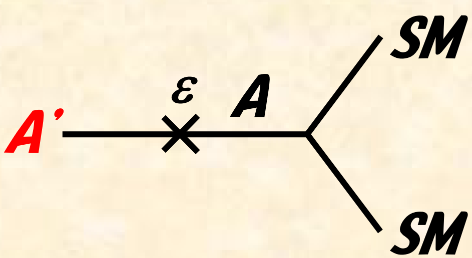
✓ Starting Lagrangian is

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

The mediator mass term is assumed to be from a Higgs mechanism.

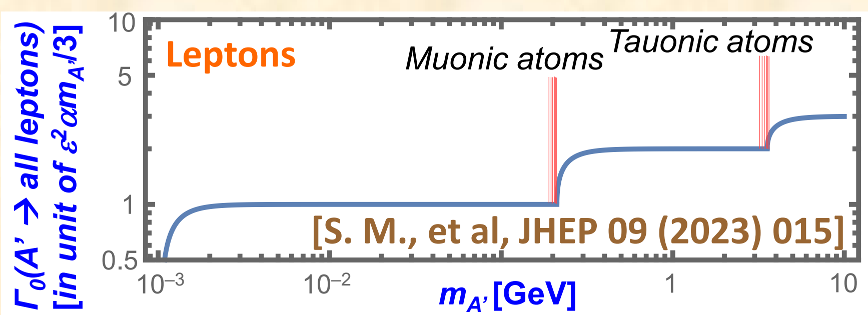
The dark photon interacts with the SM particles through the EM currents when its mass is smaller enough than the scale of EWSB.

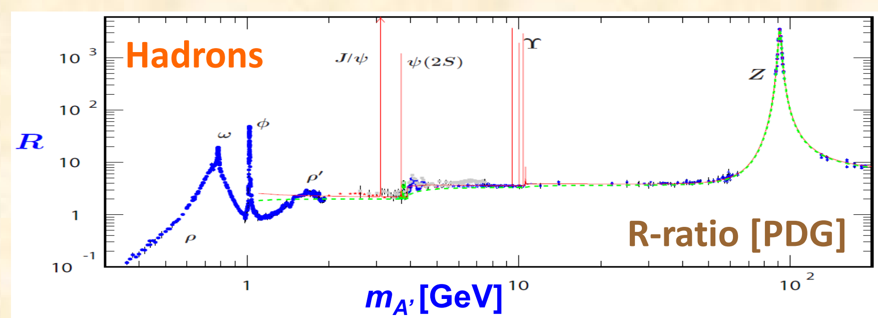
✓ Calculating its width (lifetime) @ LO ($\varepsilon \ll 1$)



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

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



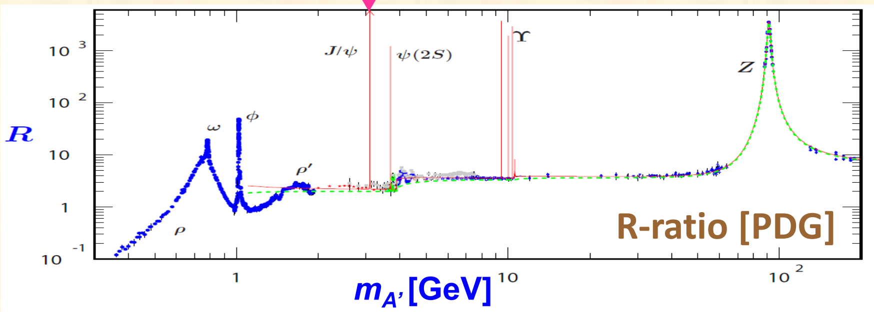


Dark photon degenerated with an SM state

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

✓ Is it possible to enhance the interaction significantly?

E.g., at here.



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

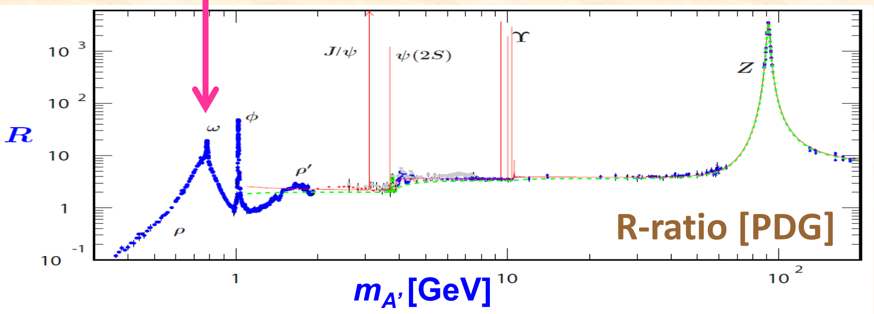
↓ Diagonalization

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

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

✓ Is the interaction enhanced significantly when the dark photon degenerates with an SM state having a large decay width?

E.g., at here.



As an SM state with a large decay width means a broad resonance, namely far from a quasi-particle, the perturbative cal. must work.

Let us consider it more carefully!

Lagrangian for A, A' and V

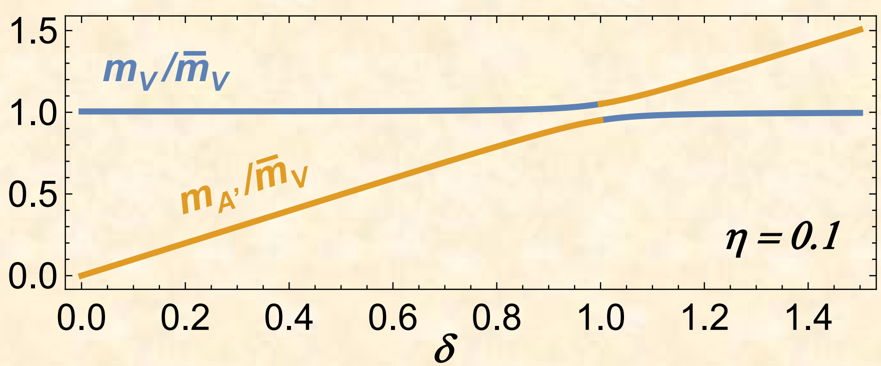
$$\mathcal{L} = -\frac{1}{4}\bar{F}_{\mu\nu}\bar{F}^{\mu\nu} - \frac{1}{4}\bar{F}'_{\mu\nu}\bar{F}'^{\mu\nu} - \frac{1}{4}\bar{V}_{\mu\nu}\bar{V}^{\mu\nu} + \frac{\epsilon}{2}\bar{F}_{\mu\nu}\bar{F}'^{\mu\nu} + \frac{\epsilon_V}{2}\bar{F}_{\mu\nu}\bar{V}^{\mu\nu} + \frac{\epsilon'_V}{2}\bar{F}'_{\mu\nu}\bar{V}^{\mu\nu}$$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

V = Z, ρ, Ps, etc.

Diagonalization

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

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



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

← 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.

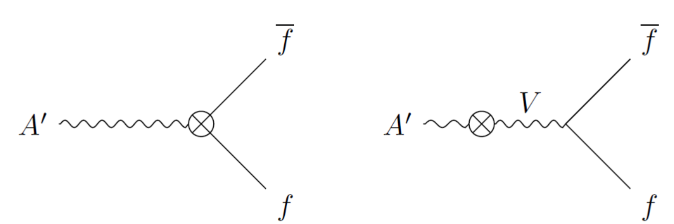
$$\mathcal{L}_{\rm int} = \left(C_{\overline{V}A'}\, g_V + C_{\overline{A}A'}\, eQ_f\right) A'_\mu \bar f \gamma^\mu f + \left(C_{\overline{V}V}\, g_V + C_{\overline{A}V}\, eQ_f\right) V_\mu \bar f \gamma^\mu f + \cdots$$

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

✓ "ε-insertion" method

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

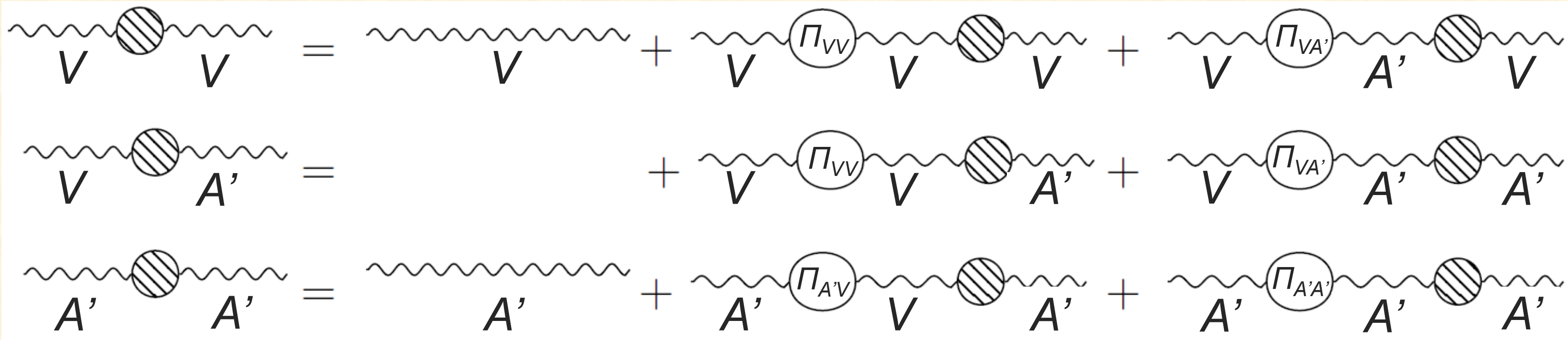
$$\Gamma_{\varepsilon I}(A' \to f\bar f) = \frac{M_{\tilde{A}'}}{16\pi^2}\frac{4}{3}\left|\bar g_f^{\tilde{A}'} + \bar g_f^{\tilde{V}} \frac{-\overline{m}_V^2 \eta}{M_{\tilde{A}'}^2 - \overline{m}_V^2 + i\overline{m}_V \overline{\Gamma}_{\tilde{V}}}\right|^2 \quad \left\{\begin{aligned} \bar g_f^{\tilde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



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

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 $\varepsilon << 1$)

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

✓ **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

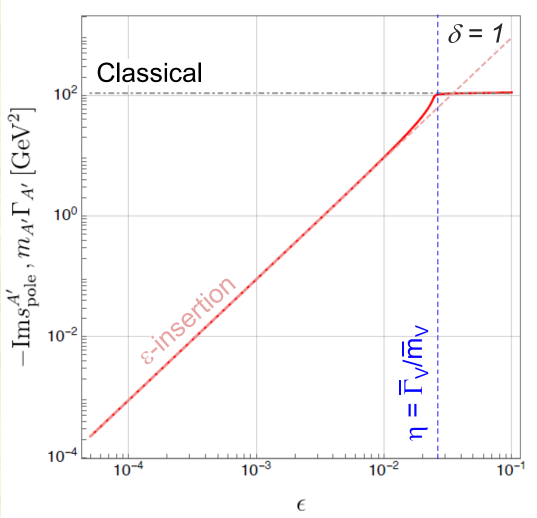
V = Z case

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

From SM theory,

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

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



Concrete examples

V = Z ca

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$\overline{\Gamma}_V$ = 2.50

From SM theo

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

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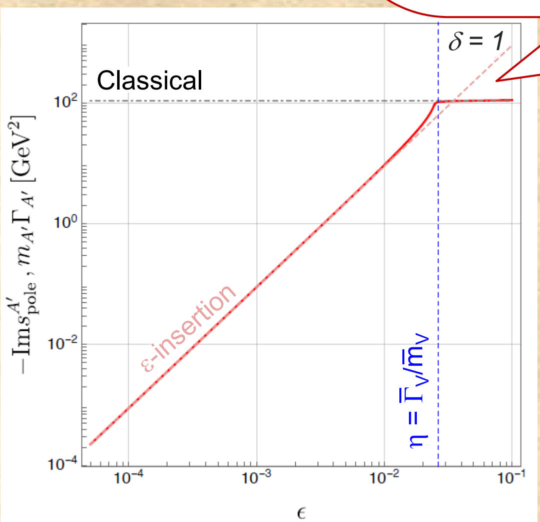
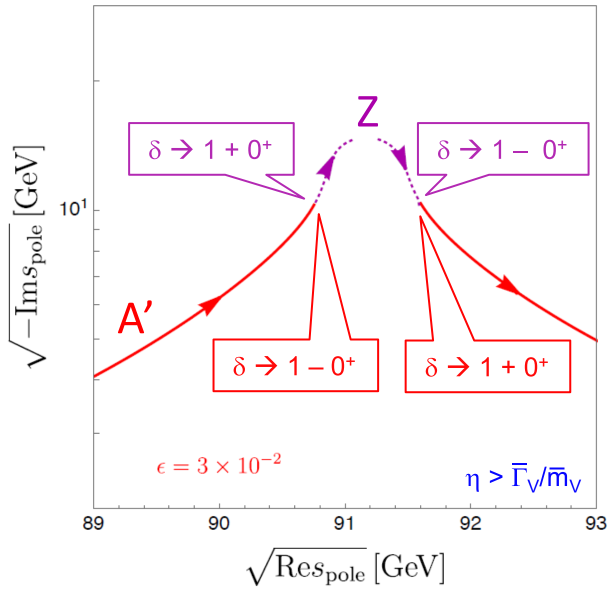
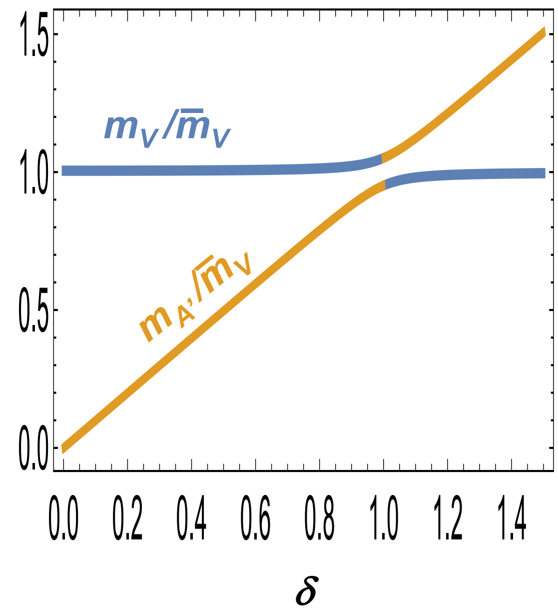


∃Level mixing





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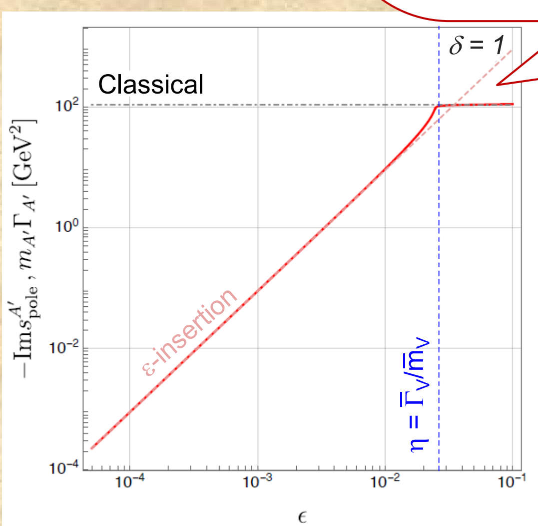

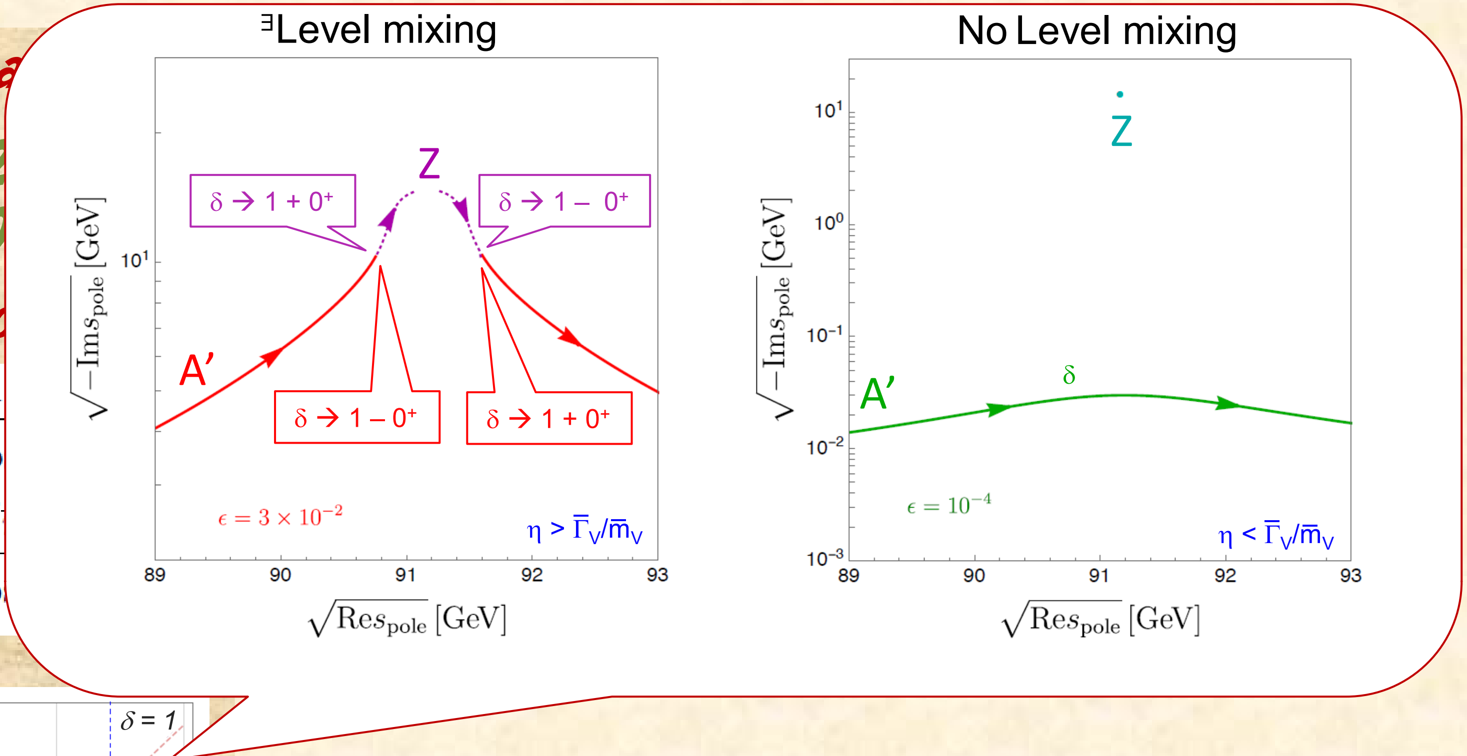

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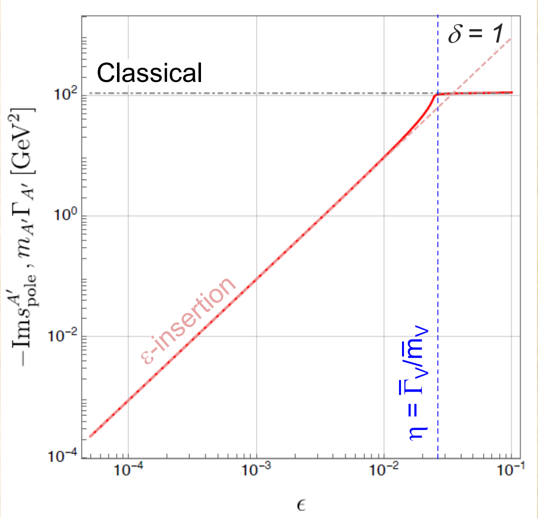


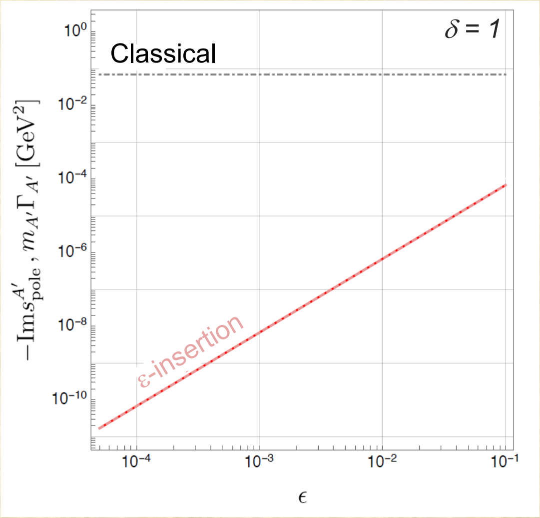
V = ρ case

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

From HLS theory,

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

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



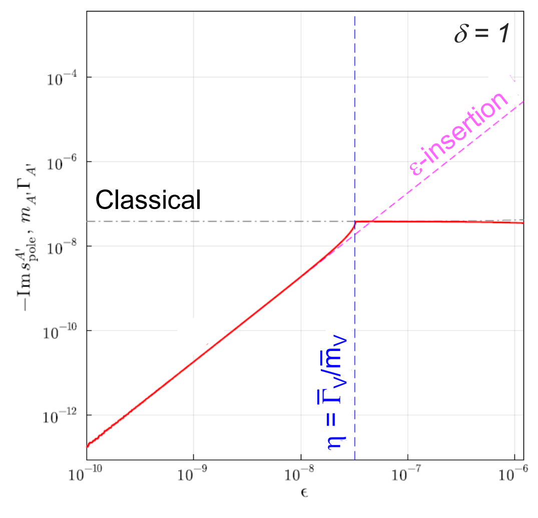
V = (μ⁻μ⁺) case

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

From NRL theory,

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

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



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**.*

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.*

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.