Mediator decay through mixing with degenerate spectrum

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I.Introduction

- **Dark sector (DS)** particles are usually assumed to **feebly interact** with SM

➡ Decays of DS into SM are highly **suppressed**

- On the other hand, when DS are degenerate with SM in mass, they are **mixed**

➡ **unsuppressed** decay due to the large mixing angle

- Feeble interaction but degenerate in SM with large decay width (e.g.mesons)

➡ DS with large decay width into SM ??

What is the boundary for suppressed / unsuppressed behavior of the decay width of a mediator particle ?

II.Mediator particle decay

We use the dark photon model

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

and evaluate its decay into SM using **3 methods** when its mass being near some vector resonance

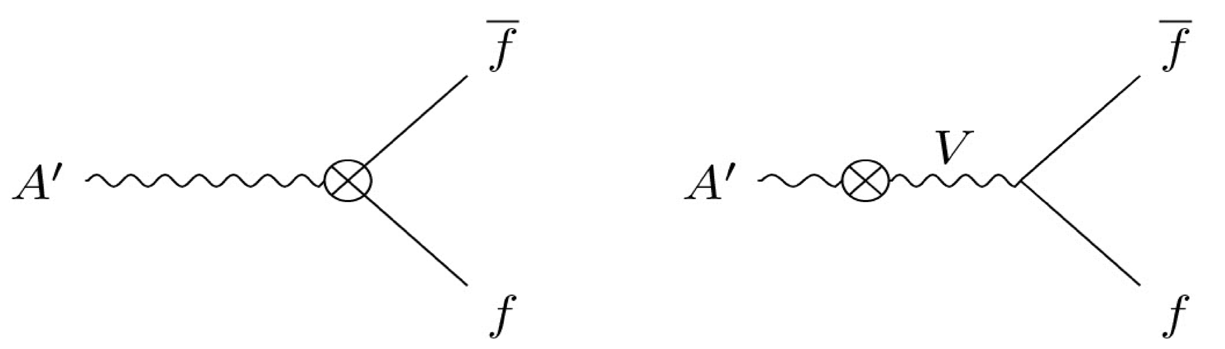
Classical method

The decay width at the tree-level in the mass basis, where all kinetic and mass mixing are removed by the field redefinition.

➡ **Unsuppressed decay width** when the dark photon mass are degenerate with the partner

Mass insertion method

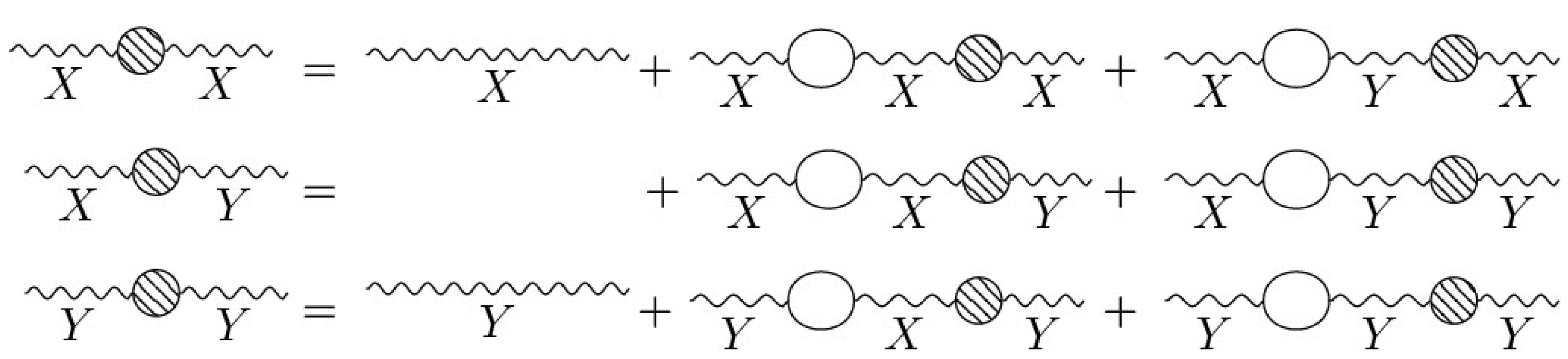
Using the mass mixing term as an interaction at once.



➡ **Suppressed decay** width even for large mixing

Pole method

Decay width determined by **the pole of scattering amplitudes** and propagators have to be russumed.



➡ **Diagonalization beyond tree level**

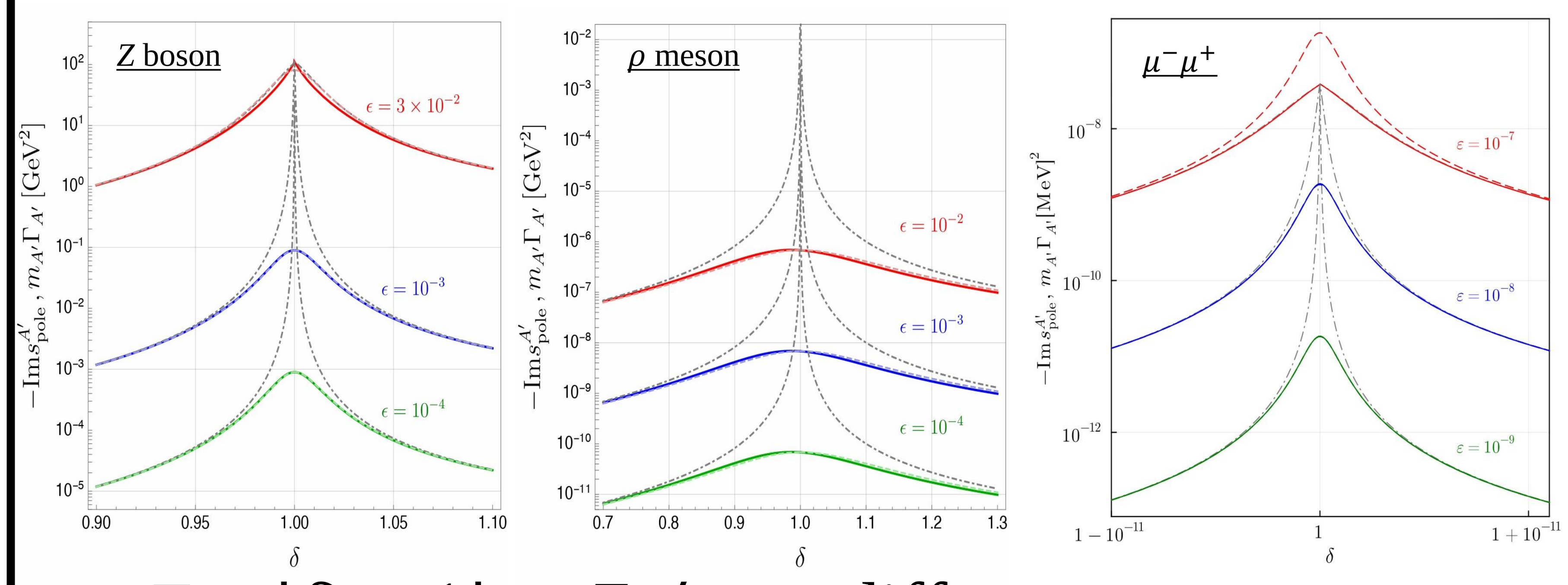
III.Mediator decay at vector resonance

We take **3 examples** of the partner of the dark photon:

- ***Z* boson**: $\Gamma_Z / m_Z \cong 0.03$ “middle” width
- ***ρ* meson**: $\Gamma_\rho / m_\rho \cong 0.2$ “large width”
- **$\mu^-\mu^+$** bound state: $\Gamma_V / m_V \cong 10^{-12}$ “small width”

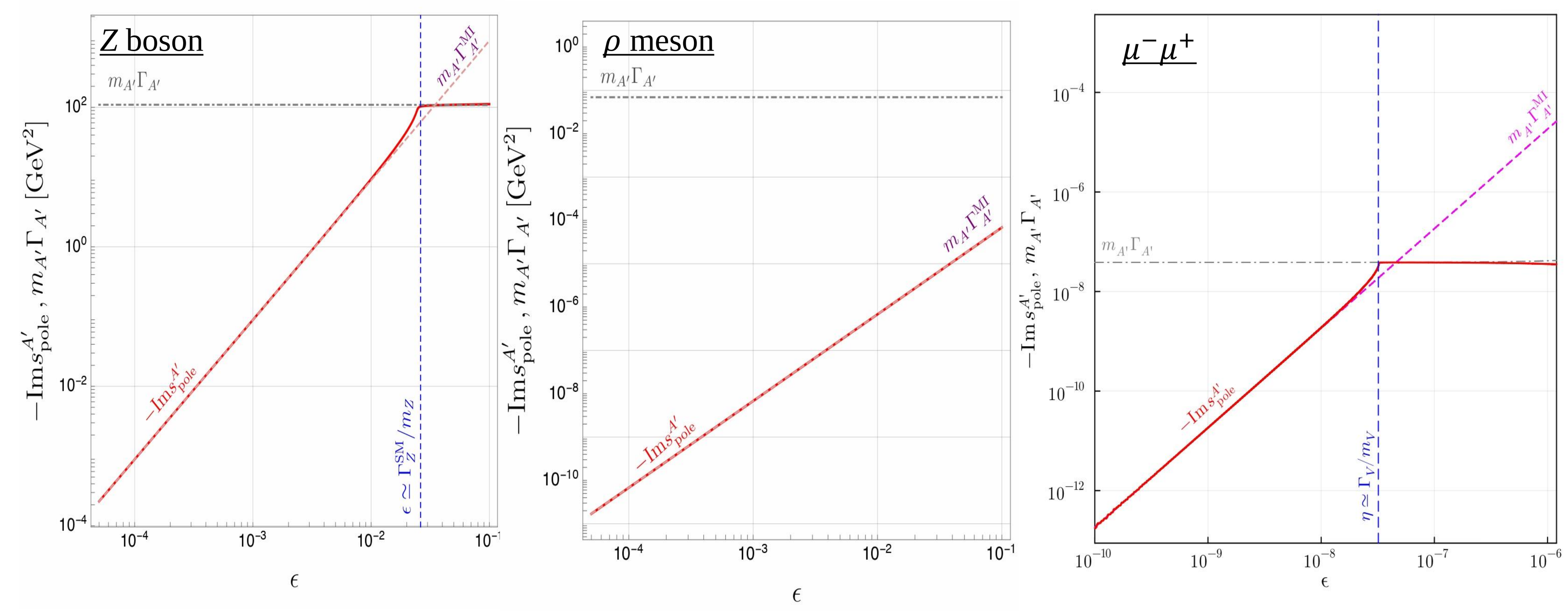
Decay widths near the resonance

Colored solid: pole, Colored dashed: mass-insertion, dot- dashed: Classical, $\delta = m_{A'}/m_V$



For $|\delta - 1| \le \Gamma_V / m_V$, differences emerge

A closer look at $\delta = 1$



We find the following criteria;

For the mixing partner V, whose effective interaction with the dark photon are given by $\mathcal{L}_{\rm int} \supset \epsilon_{\rm eff} F'_{\mu\nu}V^{\mu\nu}$

$$\begin{Bmatrix} \epsilon_{\rm eff} \ge \Gamma_V/m_V \\ \epsilon_{\rm eff} \le \Gamma_V/m_V \end{Bmatrix} \Longrightarrow \begin{Bmatrix} \text{Classical} \\ \text{Mass}-\text{insertion} \end{Bmatrix}$$

well approximates the pole width

Critical mixings for various vector mesons

Table 1: Mass, total decay width, and branching ratio to e^-e^+ of mesons, and the critical value of the kinetic mixing.

Meson	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}

IV.Summary and discussion

- We analyze the correct behavior of the decay width of the dark photon when its mass are degenerate with SM particles by introducing 3 methods for decay width.
- We found the criteria that determines the precise way to approximate the decay width of mediators.
- Application to scalar mediators in mass range 300MeV to 2 GeV are interesting due to scalar mesons.
- We may predict indirect signals for scalar mediators in such mass range.