Mediator Decays at Thresholds

Shigeki Matsumoto

(Kavli IPMU, U. Tokyo)

Collaborators: Graham White, Yu Watanabe, Yuki Watanabe

Mediator particle is often predicted in the dark sector scenario. The strength of its interactions with standard model particles is generally suppressed, especially when it is light. On the other hand, when the mediator particle decays at a threshold, i.e., its mass is close to the sum of the daughter particle's masses, the interaction strength could be much influenced. We discuss how we can take this influence into account quantitatively and how much modification we have on the interaction strength.

Dark sector scenario

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

< EW scale

Standard Model — Mediator particles — Dark sector

It plays a role in connecting the SM sector & dark sector.

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,
A mediator particle must be introduced in the theory you consider!

∵ 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.

Mediator particle

Various mediator particles are now being considered in the literature.

In particular, if the mediator particle is lighter enough than the EW scale, it is required to be a singlet under the SM gauge interactions.

The following three mediator particles are being intensively studied, as those have a renormalizable interaction with the SM particles.

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 and γ, so V couples to the SM via the EM current.

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.

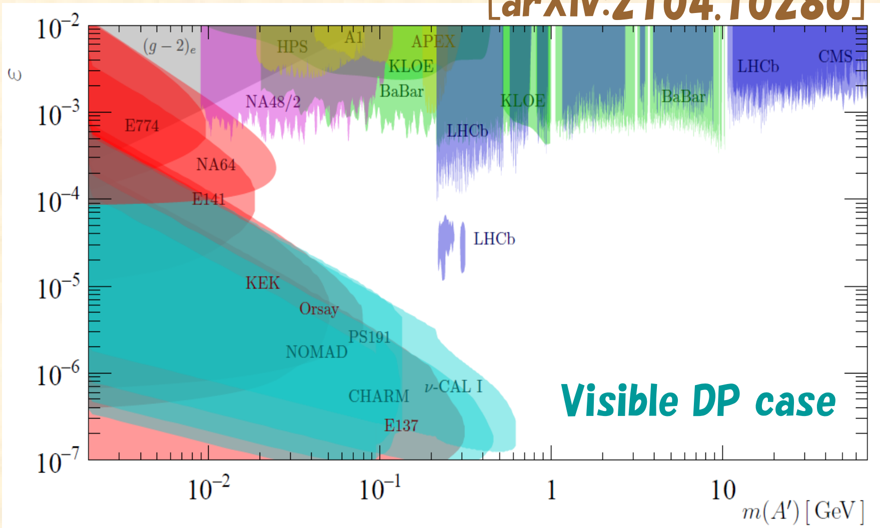
Implications to collider physics & cosmology

Light mediator particle is feebly interacting with the SM particles!

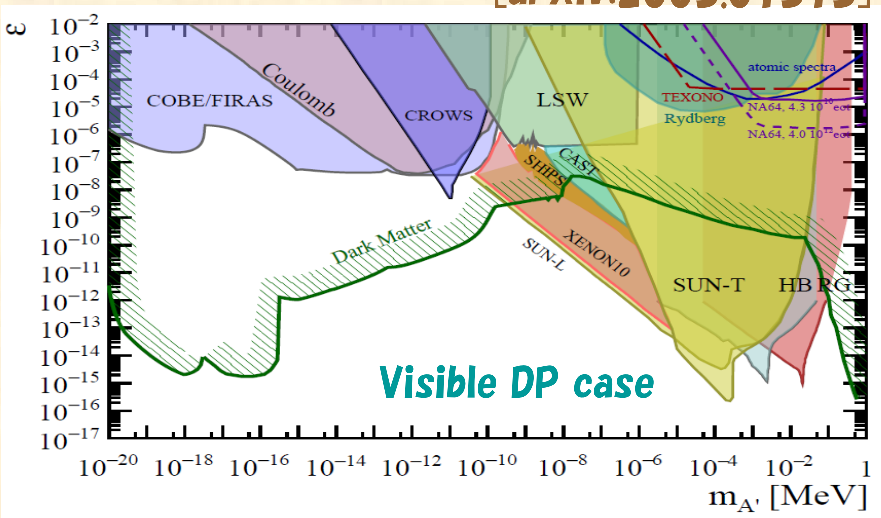
It becomes a long-lived particle at various collider experiments!

- **Typical decay modes**
  Decays into an SM particle pair, such as Med → μμ, KK, BB, etc.
- **Typical production modes**
  Direct prod., e.g., ee → Med + X.
  Boson decay, e.g., B → Med + X.

[arXiv:2104.10280]



[arXiv:2005.01515]



It could affect the evolution of the universe via its degree of freedom.

- ✓ Spoiling the successful BBN?
- ✓ Modifying CMB via its decay?
- ✓ Pulling energy out from stars?
- ✓ Modifying CMB via V ←→ γ?
- ✓ Constraints as dark matter?

Vector mediator particle

Feeble interactions of the mediator are guaranteed by small couplings. However, it is not valid when the mediator decays at a threshold, even if the mediator's interactions are suppressed by the small couplings.

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

✓ Starting Lagrangian is

$$\mathscr{L}_V = \mathscr{L}_{\rm SM} - \frac{1}{4}(V_{\mu\nu})^2 + \frac{1}{2}M_V^2(V_\mu)^2 - \frac{\xi}{2}V_{\mu\nu}B^{\mu\nu} + \cdots$$

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

✓ Making kinetic terms canonical and diagonalizing mass matrix gives

$$\mathscr{L}_V = \frac{1}{2}A'_\mu\left[(\Box + m_{A'}^2)\,g^{\mu\nu} - \partial^\mu\partial^\nu\right]A'_\nu + \frac{\epsilon\, e\, m_Z^2}{m_Z^2 - m_{A'}^2}\left[A'_\mu J^\mu_{\rm EM} + F_{A' W^\dagger W}\right] - \frac{\epsilon\,(g'/c_W)\,m_{A'}^2}{m_Z^2 - m_{A'}^2}A'_\mu J^\mu_Y + \cdots$$

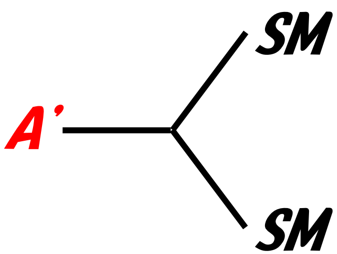
where J_{EM} and J_Y are EM and hyper-charge currents, w/ $\varepsilon = \xi \cos\theta_W$.

The vector mediator particle interacts with the SM particles through the EM currents when its mass is smaller enough than the EW scale!

Decay width of the mediator particle

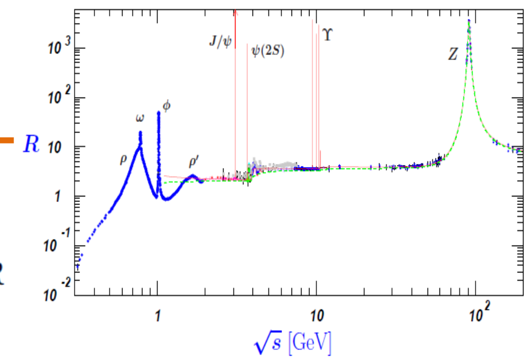
Let us consider the decay width of the mediator particle, for it gives its lifetime (relevant to collider physics) and the interaction strength between the mediator and the SM particles (relevant to cosmology).

- The mediator perturbatively decays into lepton & quark pairs at LO:

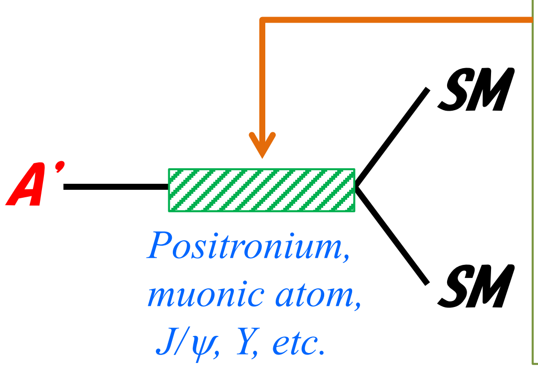


$$\Gamma_0(A' \to \ell_i^- \ell_i^+) \simeq \epsilon^2 \frac{\alpha m_{A'}}{3} \left(1 + 2\frac{m_{\ell_i}^2}{m_{A'}^2}\right) \sqrt{1 - \frac{4m_{\ell_i}^2}{m_{A'}^2}}$$

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



- Non-perturbative effect becomes sizable at the threshold region.



Threshold singularities (Sommerfeld effect, bound states) caused by long-range forces.

Singularities appear not only for the quark final states (via QCD force) but also for the leptonic final states (via Coulombe force).

Quantitative description

Let us consider how such an effect is quantitatively described using an example that A' decays into a bottom quark pair at the threshold.

Recipe … The use of the potential non-relativistic (pNR) lagrangian:

1. Integrating out long-range force fields from the Lagrangian.
2. NR-expand the (nearly) on-shell part of the bottom quark field.
3. Introducing auxiliary fields describing the two-body states of $b\bar{b}$.
4. Integrating out the NR-expanded bottom quark field.

$$\mathcal{L}_V^{(\mathrm{pNR})} \simeq -\frac{1}{2}\vec{A}'(\Box + m_{A'}^2)\vec{A}' + \int d^3r\,\vec{\chi}^\dagger(\vec{r},x)\left(i\partial_{x^0} + \frac{\nabla_x^2}{4m_b} + \frac{\nabla_r^2}{m_b} - V(\vec{r})\right)\vec{\chi}(\vec{r},x)$$
$$+ \sqrt{2/3}\,\epsilon e\vec{A}'\left[e^{2im_b x^0}\vec{\chi}^\dagger(\vec{0},x) + e^{-2im_b x^0}\vec{\chi}(\vec{0},x)\right] + \cdots$$

Here, c(r, x) is the field describing the two-body states of $b\bar{b}$.

5. Decomposing the two-body field in terms of the partial waves.

$$\mathcal{L}_V^{(\mathrm{pNR})} \simeq -\frac{1}{2}\vec{A}'(\Box + m_{A'}^2)\vec{A}' + \sum_i \bar{f}_i(i\not{D} - m_{f_i})f_i - \sum_n \frac{1}{2}\vec{\varphi}_n(\Box + m_{\varphi_n}^2)\vec{\varphi}_n$$
$$+ e\sqrt{\frac{2m_b}{3\pi}}\left[\epsilon\vec{A}' - ie\sum_i\int d^4y\,Q_i\,\mathcal{G}^{(\gamma)}(x-y)\bar{f}_i(y)\vec{\gamma}f_i(y)\right]\cdot\sum_n R_{n00}(0)\,\vec{\varphi}_n$$

Mixing!

Radial wave fn.

φ_n is a partial wave component w/ 1^{--} quantum number (Υ meson). Note that no continuum states exist due to the color consignment.

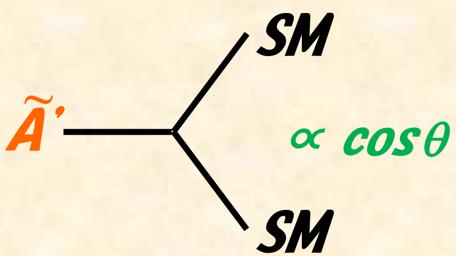
Mixing & Decays

When m_{φ_n} becomes very close to $m_{A'}$, the perturbative calculation of the width breaks down, and we have to diagonalize the mass matrix:

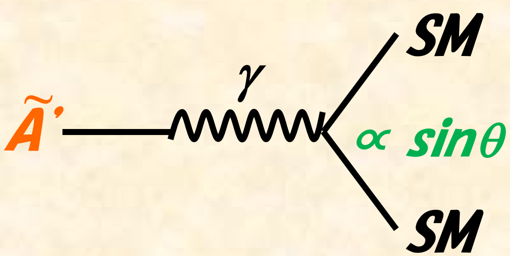
$$\begin{pmatrix} \vec{\tilde{A}}' \\ \vec{\tilde{\varphi}}_n \end{pmatrix} = \begin{pmatrix} \cos\vartheta_n & -\sin\vartheta_n \\ \sin\vartheta_n & \cos\vartheta_n \end{pmatrix} \begin{pmatrix} \vec{A}' \\ \vec{\varphi}_n \end{pmatrix}$$

Then the interaction of the mediator particle becomes

$$\mathscr{L}_V^{(\mathrm{pNR})} \simeq -e\vec{\tilde{A}}' \cdot \sum_i Q_i \int d^4y \left[\epsilon \cos\vartheta_n\, \delta(x-y) - ie\sin\vartheta_n \sqrt{\frac{2m_b}{3\pi}} R_{n00}(0)\, \mathscr{G}^{(\gamma)}(x-y) \right] \bar{f}_i(y)\vec{\gamma} f_i(y)$$



+



Originating in the A' int. | Originating in the Υ int.

Other interactions originating in those of the Υ mesons are

$\Upsilon \to l^- l^+$ (lepton pairs)

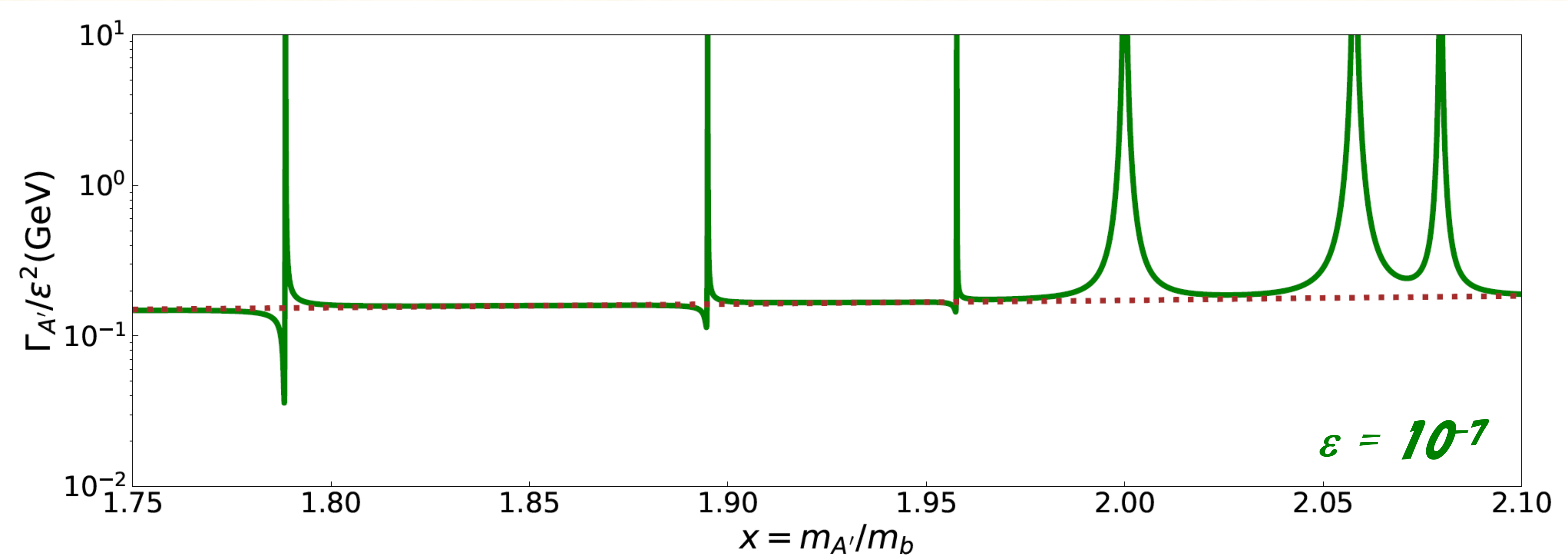
$\Upsilon \to qq$ (light hadrons)

$\Upsilon \to ggg, gg\gamma$, (3 gauge bosons)

$\Upsilon(nS) \to \Upsilon(mS) + X$ (with $n > m$) [De-excitation process]

$\Upsilon \to$ B meson pairs ($m_\Upsilon > 2m_B$)

Result & Summary



We have quantitatively estimated **the threshold singularity effect** on the interaction strength (total decay width) of the vector mediator particle when its mass is close to those of upsilon mesons. We have given a formalism to quantitatively describe this effect based on **pNR** and found that the effect **could be sizable**. The same effect will appear for another mass and another type of mediator particle whenever it decays at the threshold with a final state feeling long-range force.