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Quarkonia in Lepton Flavor Violation

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arXiv:2405.01782

"Más allá del Modelo Estándar y Astropartículas"
Instituto de Física - 29 septiembre al 1 octubre

Content

- Motivation
- Hadronic de-excitation and Lepton Flavor Violation (LFV)
- Results
- Conclusions

Experiments measuring LFV

- MEG II ($\mu \to e\,\gamma$)

  A. M. Baldini et al.
  arXiv:1801.04688

- Mu3e ($\mu \to eee$)

  K. Arndt et al.
  arXiv:2009.11690

- COMET ($\mu \to e$) (quizá este no va aquí, es un proceso de núcleos)

  R. Abramishvili et al.
  arXiv:1812.09018

Purely leptonic

- BELLE II ($B_s^0 \to \tau^\pm l^\mp$)

  L. Nayak et al.
  arXiv:2301.10989

- LHCb ($B^0(b\bar{d}) \to \tau^\pm \mu^\mp, B_s^0(b\bar{s}) \to \tau^\pm \mu^\mp$)

  R. Aaij et al.
  arXiv:1905.06614

- BES III ($J/\psi \to e\tau$)

  M. Ablikim et al.
  arXiv:2103.11540

Hadronic

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Motivation

- Lepton Flavor Violation (LFV) in Standard Model Extensions: $\mu \rightarrow e\gamma$ (leptons only)
- Hadronic processes: $V \rightarrow P\gamma$ $(\rho \rightarrow \pi\gamma)$, de-excitations: $V' \rightarrow V\gamma \rightarrow V\, l_i^+\, l_j^-$
- Previous hadronic transitions involving b → s transitions: $B_{(d\bar{b})} \rightarrow K_{(d\bar{s})}\, l_i^+\, l_j^-$ [1].
- Hadronic de-excitations with no changing in quark content (not studied yet).

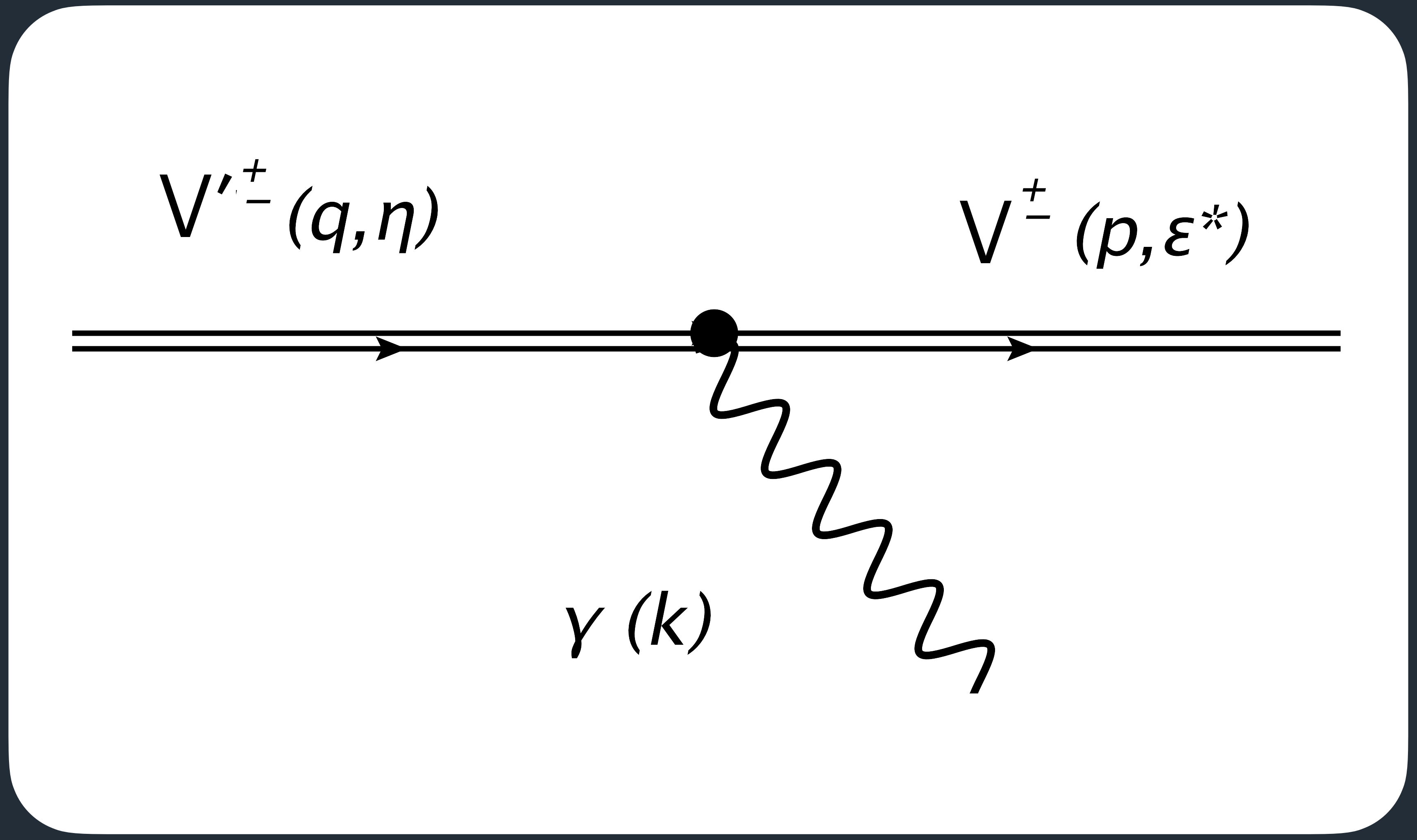
Combining these ideas, we propose the study of Hadronic de-excitations with LFV:

$$V' \rightarrow V\, l_i^+\, l_j^-, P' \rightarrow P\, l_i^+\, l_j^-$$

[1] arXiv:2303.07521, arXiv:2312.05071

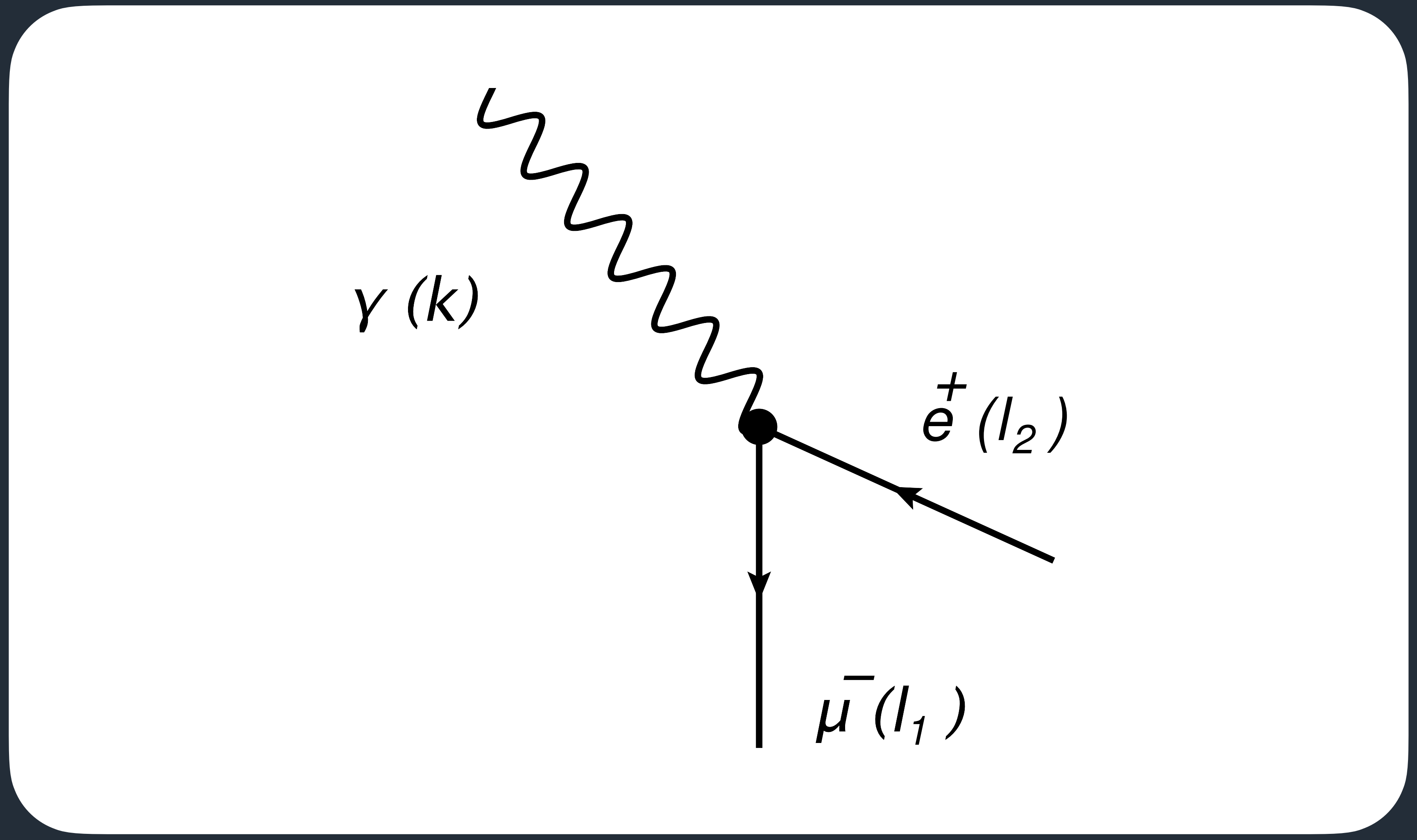
Hadronic de-excitation and LFV

Hadronic de-excitation



(same initial and final quarks)

Lepton Flavor Violation (LFV)

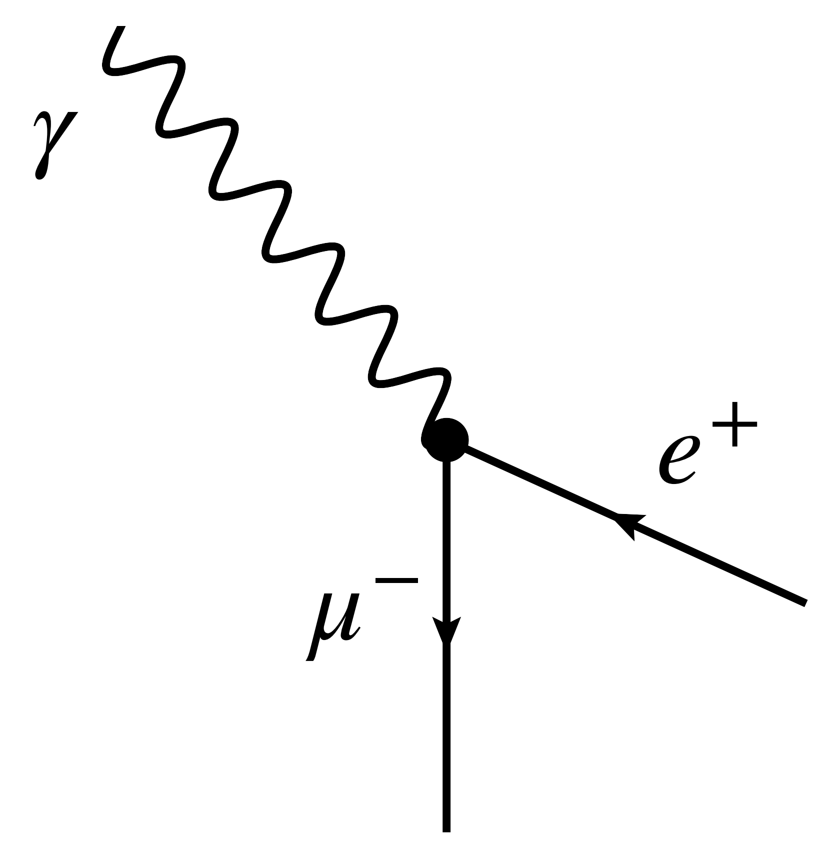


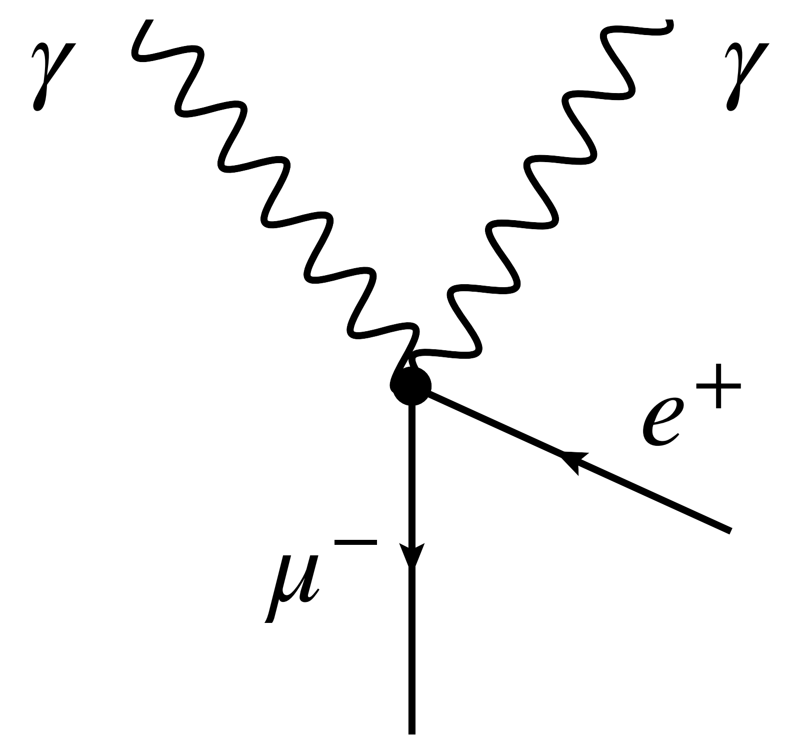
Not allowed in the SM

LFV: Effective Theory with dim-5 and dim-7 operators

$$\mathscr{L}_{dim-5} = D_R^{\mu e}\,\bar{\mu}_L \sigma_{\mu\nu} e_R F^{\mu\nu} + D_L^{\mu e}\,\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + h.c.$$

$$\mathscr{L}_{dim-7} = (G_{SR}^{\mu e}\bar{\mu}_L e_R + G_{SL}^{\mu e}\bar{\mu}_R e_L)F_{\mu\nu}F^{\mu\nu} + (\tilde{G}_{SR}^{\mu e}\bar{\mu}_L e_R + \tilde{G}_{SL}^{\mu e}\bar{\mu}_R e_L)\tilde{F}_{\mu\nu}F^{\mu\nu} + h.c.$$





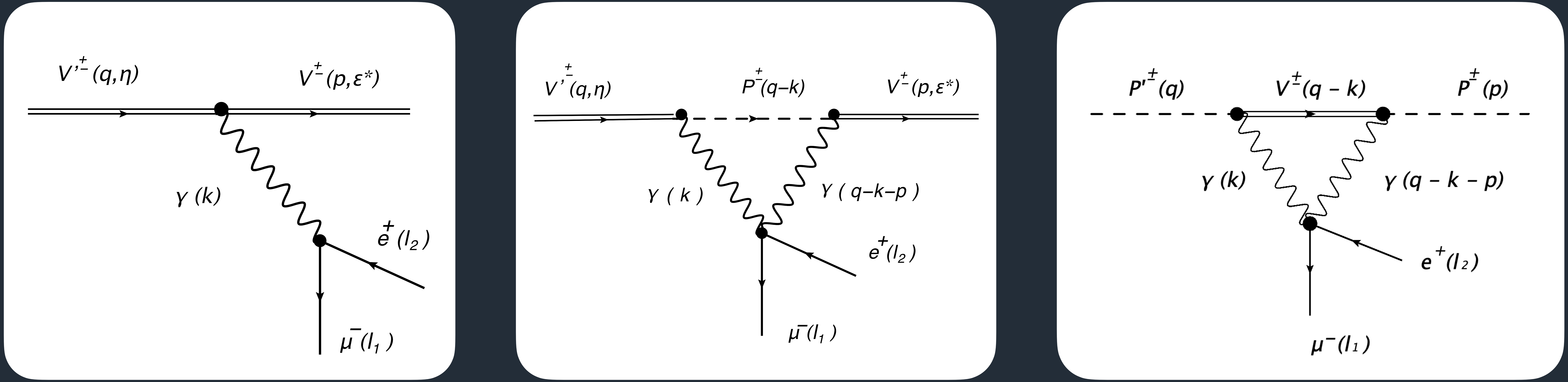
Wilson Coefficients

Coefficient	Constraint
$\lvert D^{\mu e} \rvert$	3.1×10^{-14} GeV^{-1}
$\lvert G_{\mu e} \rvert$	1.1×10^{-10} GeV^{-3}

Indirect upper limits on $l_i \to l_j \gamma \gamma$ from $l_i \to l_j \gamma$

F. Fortuna, A. Ibarra, X. Marcano, M. Marín, and P. Roig,, Phys. Rev. D 107, 015027 (2023), arXiv:2210.05703

$V' \to V\mu e$ | $V' \to V\mu e$ | $P' \to P\mu e$



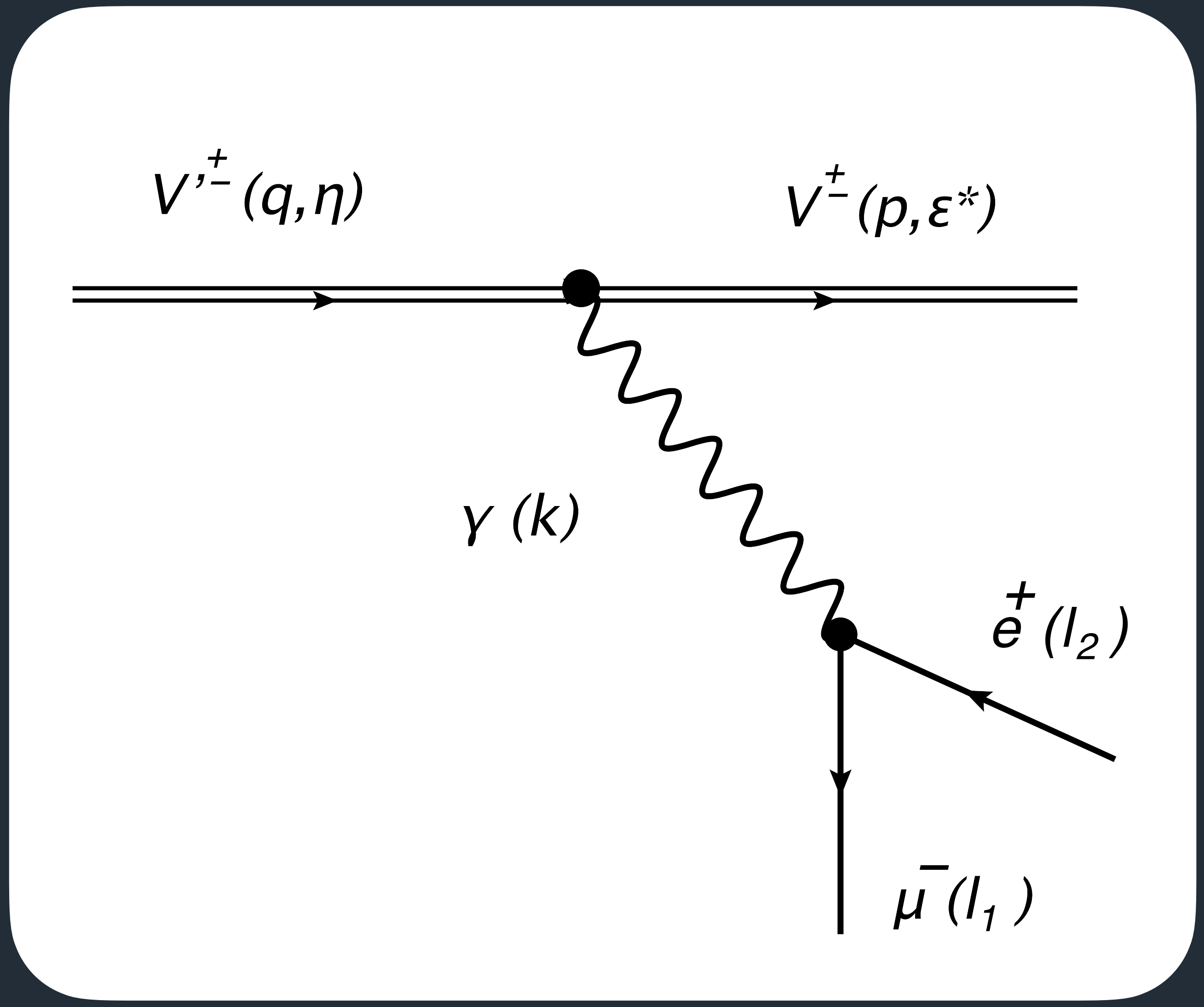
dim-5 | dim-7 (EM and Dual EM) | dim-7

In addition to light quarks, we integrate Quarkonia $(b\bar{b}, c\bar{c})$:

$V' : \Upsilon(2S),\ \psi(2S),\ \rho'$ $\quad$ $P' : \eta_c(2S),\ \eta_b(2S)$

$V : \Upsilon(1S),\ \psi(1S),\ \rho$ $\quad$ $P : \eta_c(1S),\ \eta_b(1S),\ \pi$

Decay $V' \to V \mu e$, dim-5 operator



$$\mathcal{M}_{\text{dim5}} = -\frac{e\, g_{V'V\gamma}}{k^2}\ell_{\mu\nu}(k^\mu g^{\nu\gamma} - k^\nu g^{\mu\lambda})\,\Gamma_{\alpha\beta\gamma}(q,k)\,\eta^\alpha \epsilon^{*\beta}$$

Leptonic part: $\ell_{\mu\nu} = \bar{u}_1 \sigma_{\mu\nu}(D_R^{\mu e} P_R + D_L^{\mu e} P_L) v_2$

Possible effective couplings: $g_{\rho'\rho\gamma}$, $g_{\Upsilon(2S)\Upsilon(1S)\gamma}$, $g_{\psi(2S)\psi(1S)\gamma}$

EM Vertex:

$$\Gamma^{\alpha\beta\gamma}(q,k) = \beta(g^{\alpha\beta}k^\gamma - g^{\gamma\alpha}k^\beta) + \frac{\gamma}{2m_{V'}^2}\left[(2q-k)^\gamma k^\alpha k^\beta - q\cdot k(g^{\beta\gamma}k^\alpha + g^{\gamma\alpha}k^\beta)\right]$$

Magnetic dipole moment

$\beta = 2$

Electric quadrupole

$\gamma = 1$

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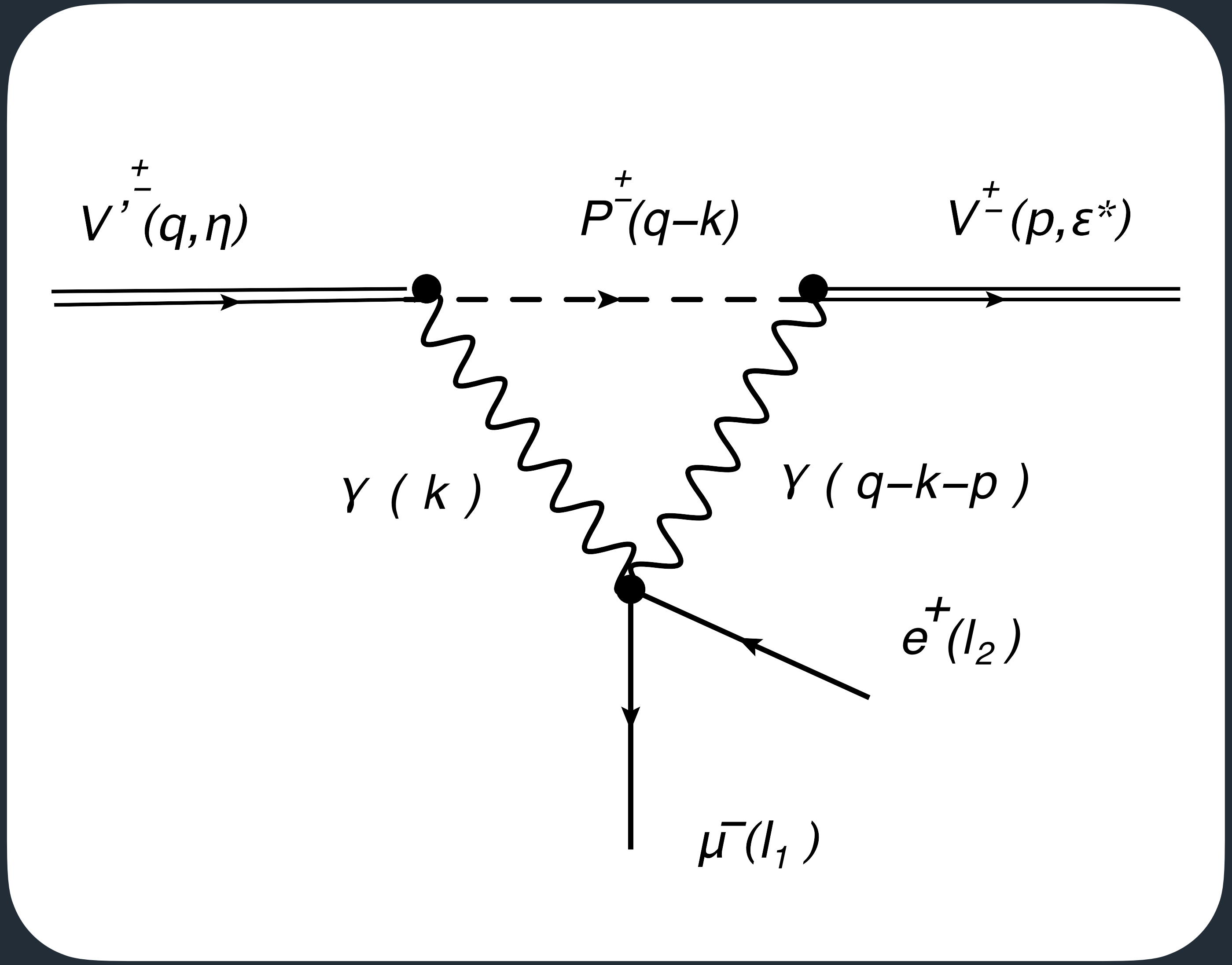
Decay $V' \to V\mu e$, dim-7 operator



Effective Vector-Vector-Pseudoscalar coupling:

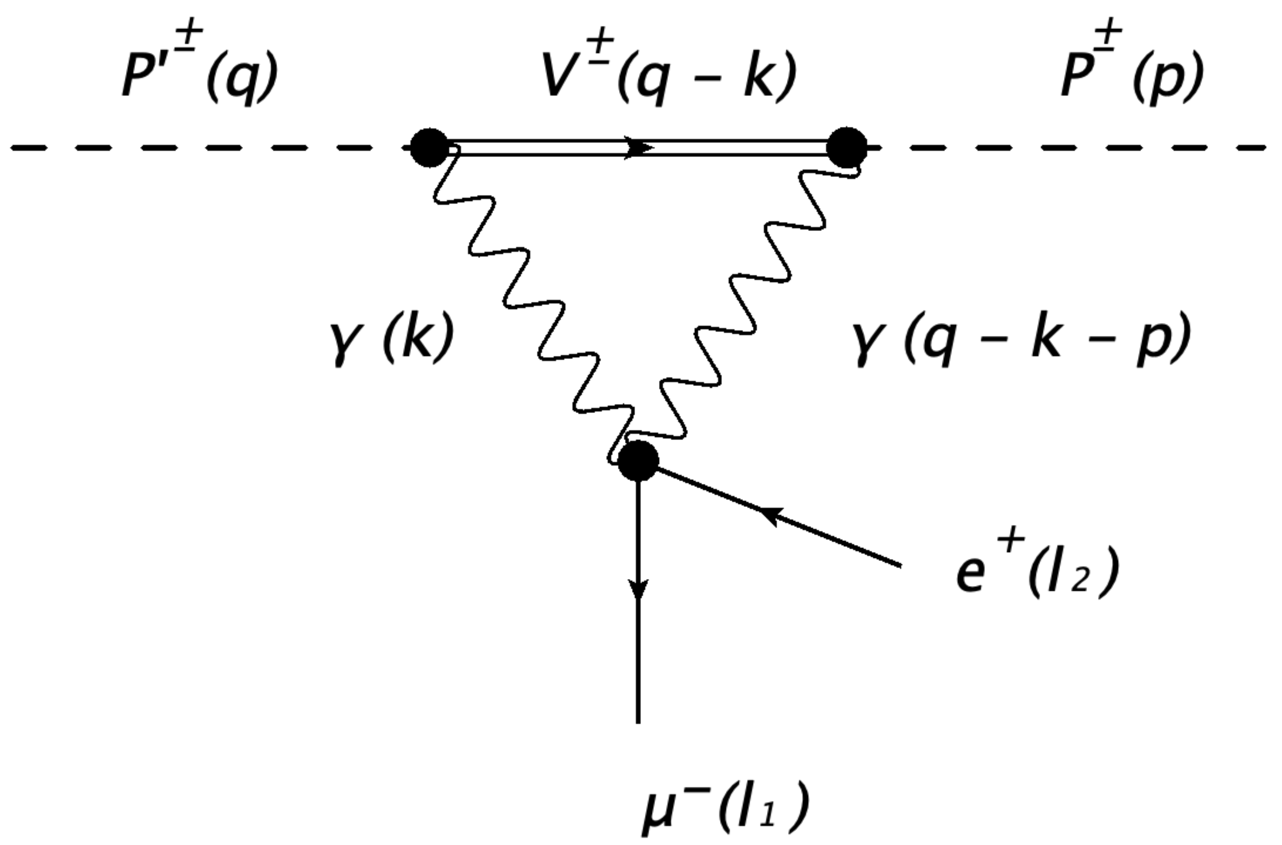
$$\mathscr{L} = g_{VP\gamma}\, \epsilon_{\alpha\beta\mu\nu}\, \partial^\alpha V^\beta \partial^\mu A^\nu P$$

$$\mathscr{M}_{dim7(F)} = 2\ell^F \Gamma^F_{\alpha\beta} \eta^\alpha \epsilon^{*\beta} \qquad \mathscr{M}_{dim7(\tilde{F})} = 2\ell^{\tilde{F}} \Gamma^{\tilde{F}}_{\alpha\beta} \eta^\alpha \epsilon^{*\beta}$$

Effective couplings: $g_{\rho'\pi\gamma}, \quad g_{\Upsilon\eta_b\gamma}, \quad g_{\psi\eta_c\gamma}$

$$\Gamma^F_{\alpha\beta} = \frac{i g_{V'P\gamma}\, g_{VP\gamma}}{16\pi^2} \left\{ f_1(m_{12}^2)\, p_\alpha\, q_\beta + f_2(m_{12}^2)\, g_{\alpha\beta} \right\} \qquad \Gamma^{\tilde{F}}_{\alpha\beta} = \frac{i g_{V'P\gamma}\, g_{VP\gamma}}{16\pi^2} \epsilon_{\alpha\beta\mu\nu}\, p^\mu\, q^\nu f_3(m_{12}^2)$$

Decay $P' \to P\mu e$, dim-7 operator



$$\mathscr{M}_{dim7(F)} = \frac{i g_{P'V\gamma}\, g_{PV\gamma}}{4\pi^2}\, \ell^F f_4(m_{12}^2)$$

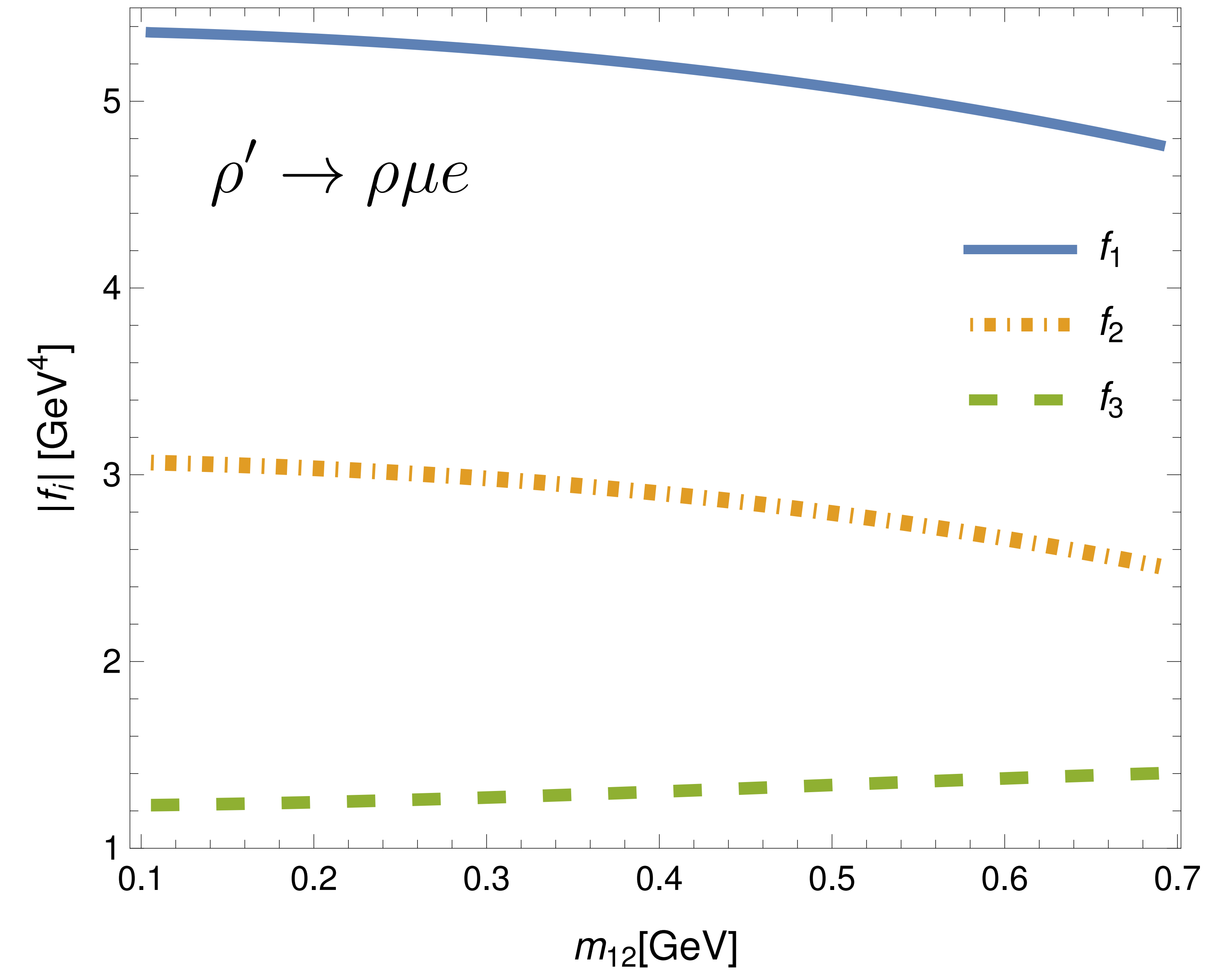
Effective couplings: $g_{\Upsilon\eta_b\gamma}, \quad g_{\psi\eta_c\gamma}$

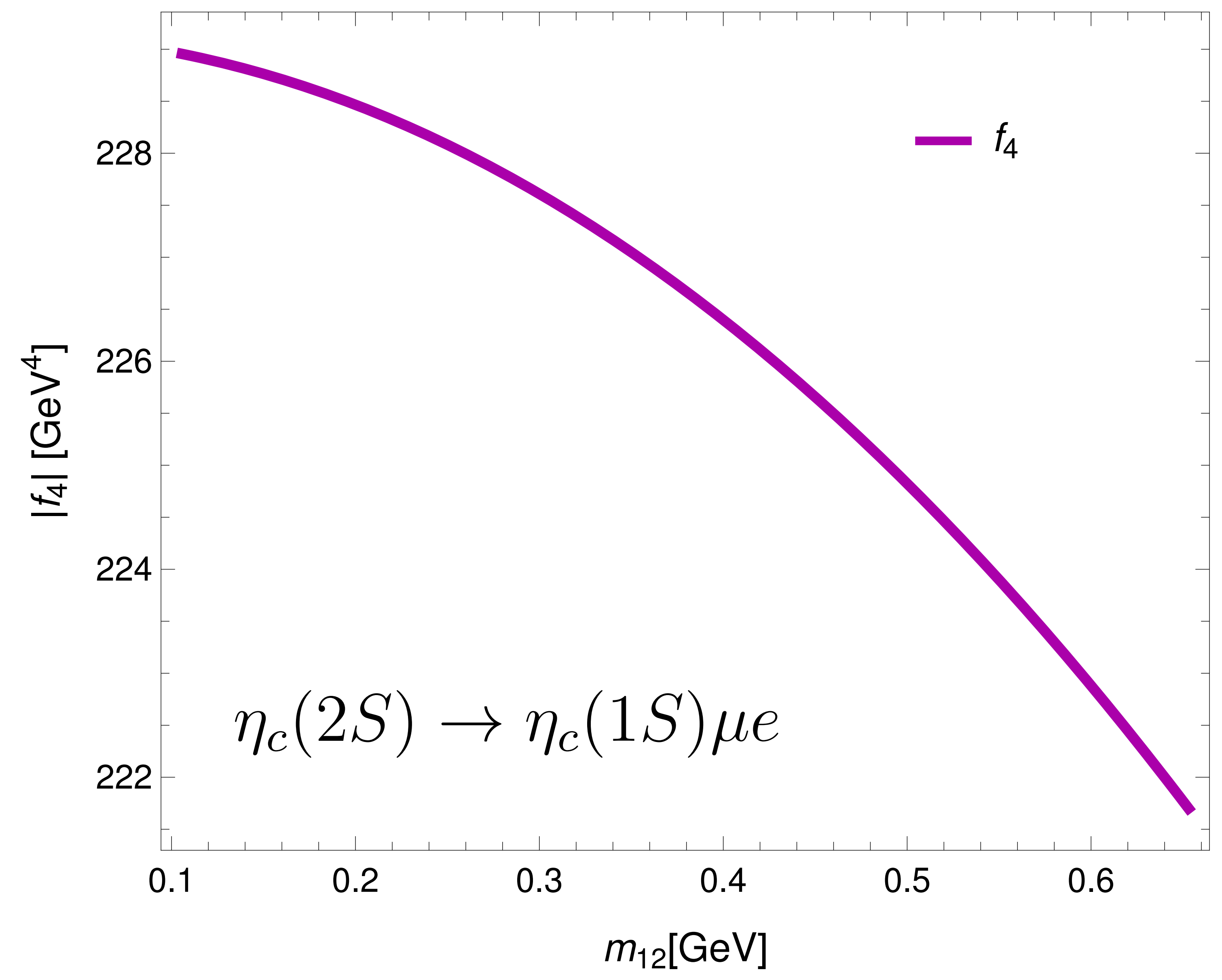
Loop functions f_1, f_2, f_3, f_4

$$\Gamma^{F}_{\alpha\beta} = \frac{i g_{\rho'\pi\gamma}\, g_{\rho\pi\gamma}}{16\pi^2} \left\{ f_1(m_{12}^2)\, p_\alpha\, q_\beta + f_2(m_{12}^2)\, g_{\alpha\beta} \right\}$$

$$\Gamma^{\tilde{F}}_{\alpha\beta} = \frac{i g_{\rho'\pi\gamma}\, g_{\rho\pi\gamma}}{16\pi^2} \epsilon_{\alpha\beta\mu\nu}\, p^\mu\, q^\nu\, f_3(m_{12}^2)$$

$$\mathcal{M}_{dim7(F)} = \frac{i g_{V'P\gamma}\, g_{VP\gamma}}{4\pi^2}\, \ell^F f_4(m_{12}^2)$$





f_1 and f_3 are multiplied by $p \cdot q$ to be dimensionally consistent with f_2

Results

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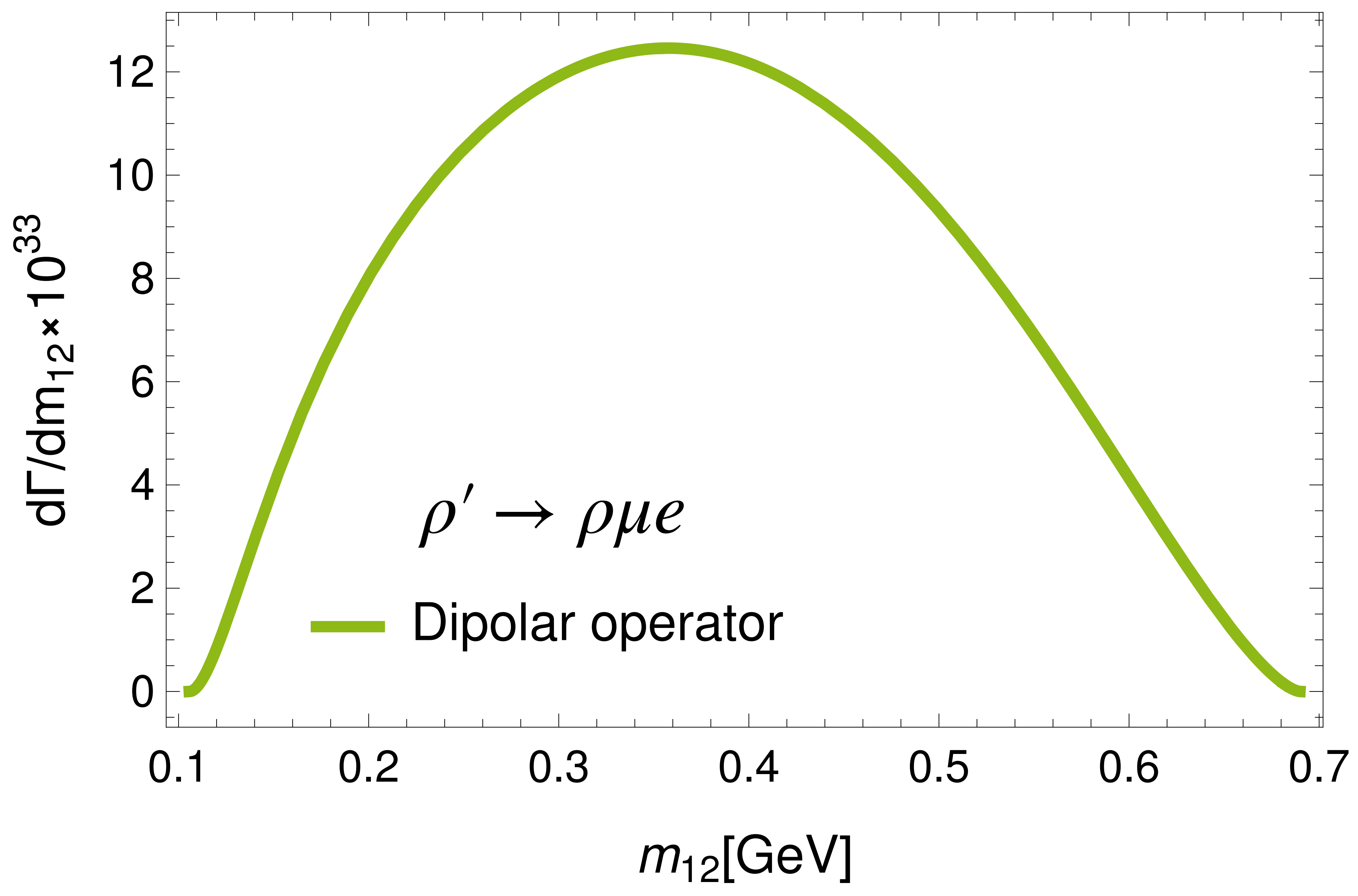
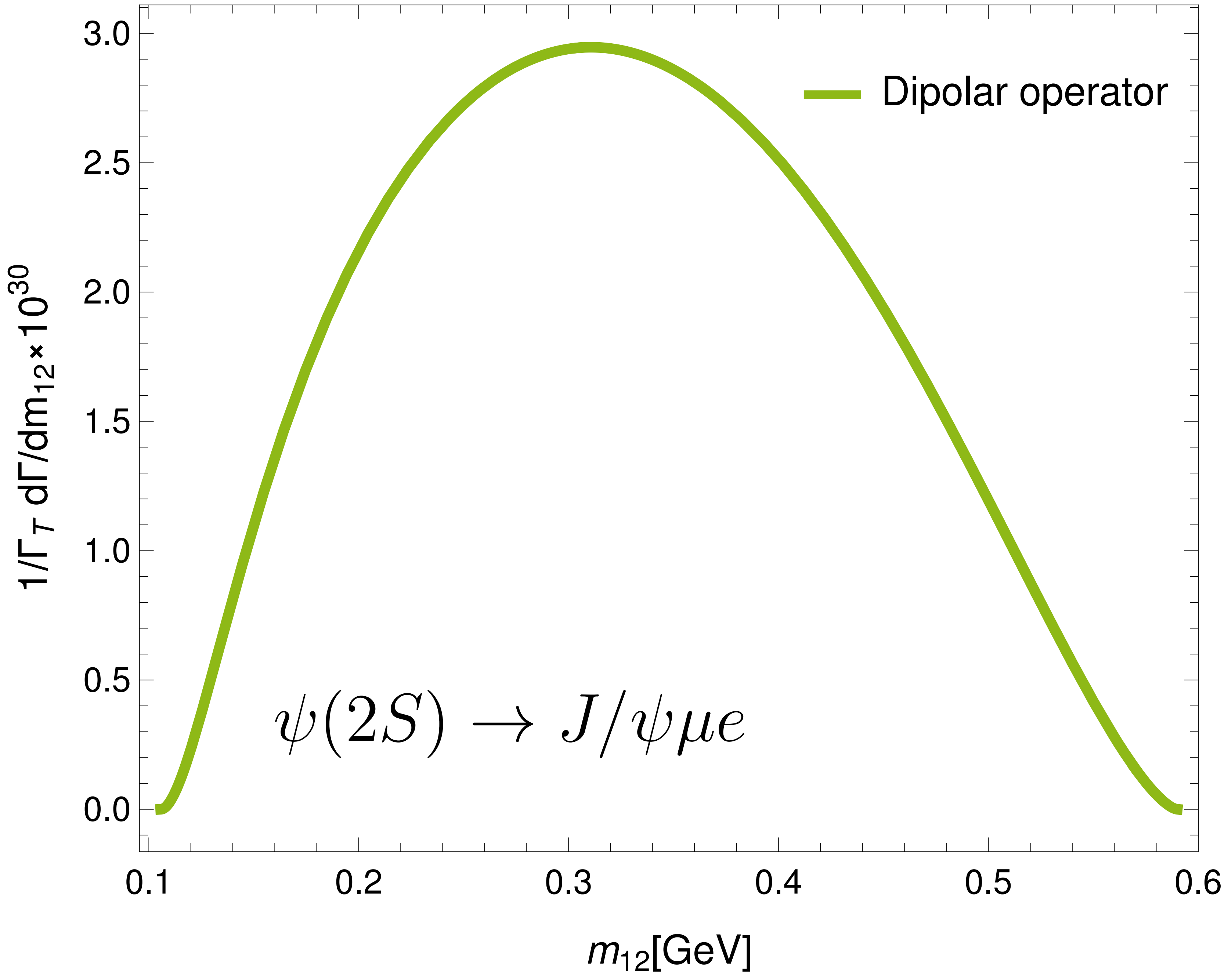
dim-5

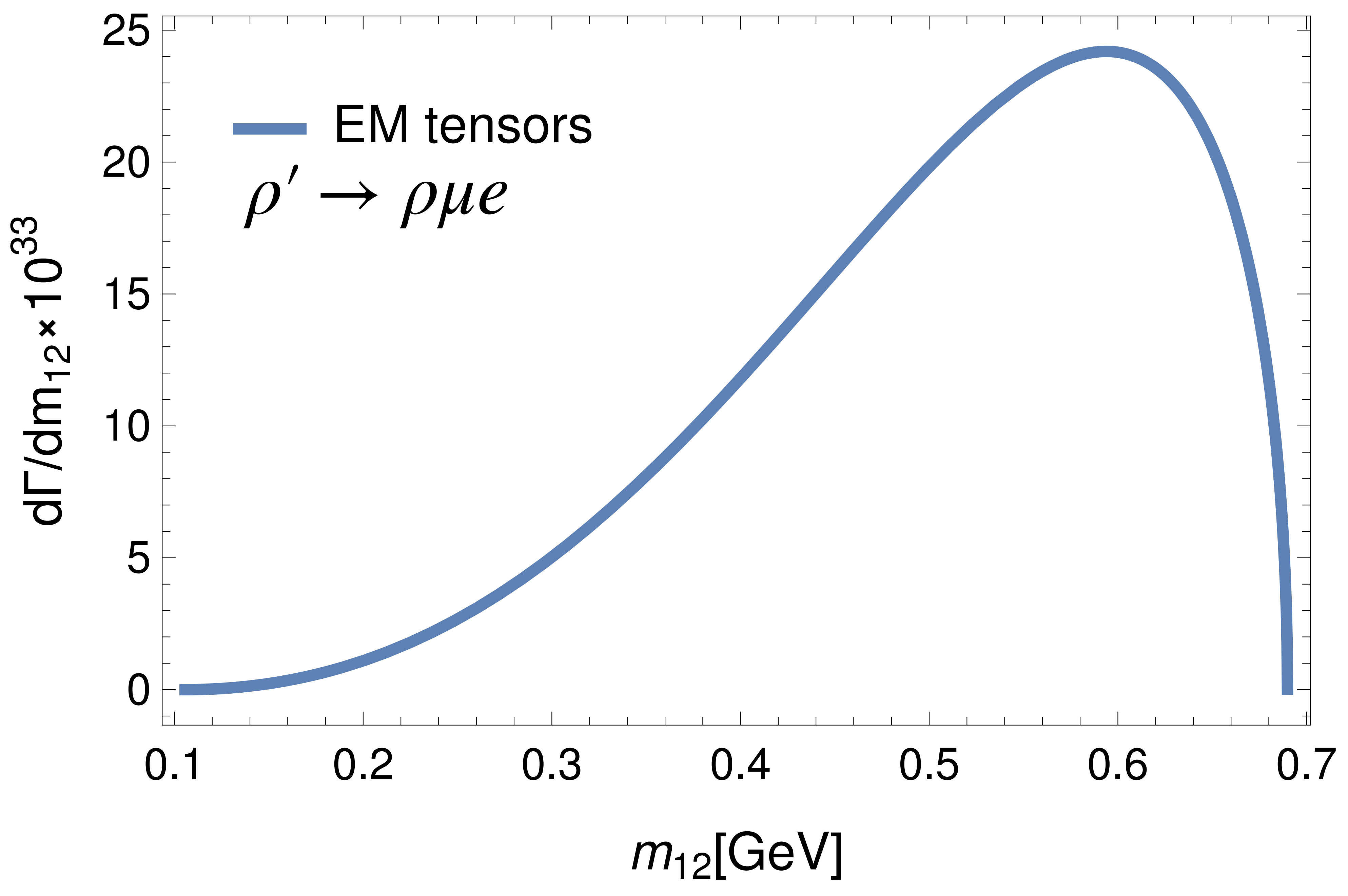
Differential decay rate $\frac{d\Gamma}{dm_{12}}$ with respect to the invariant dilepton mass $m_{12}^2 = (l_1 + l_2)^2$

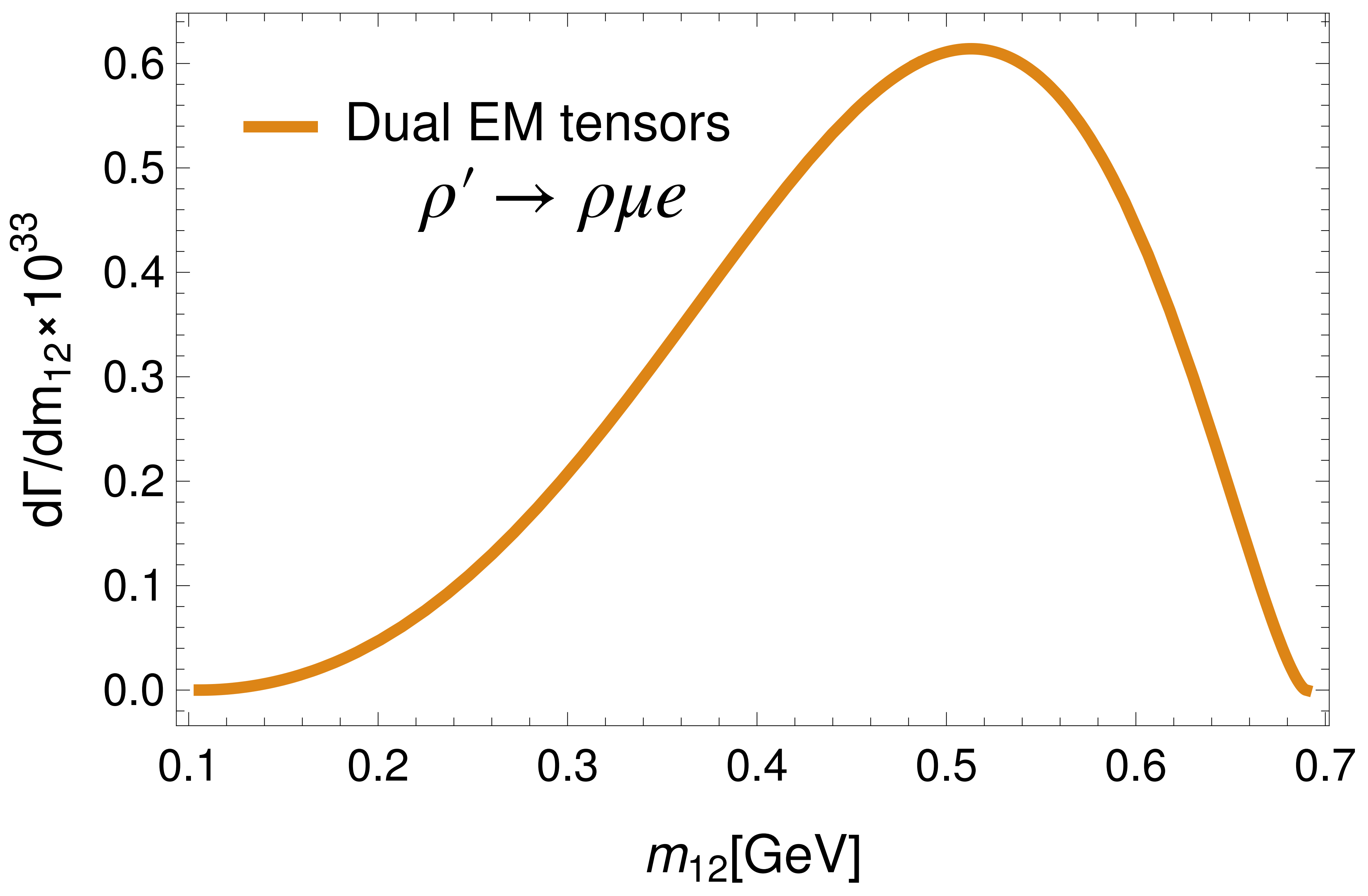




dim-7

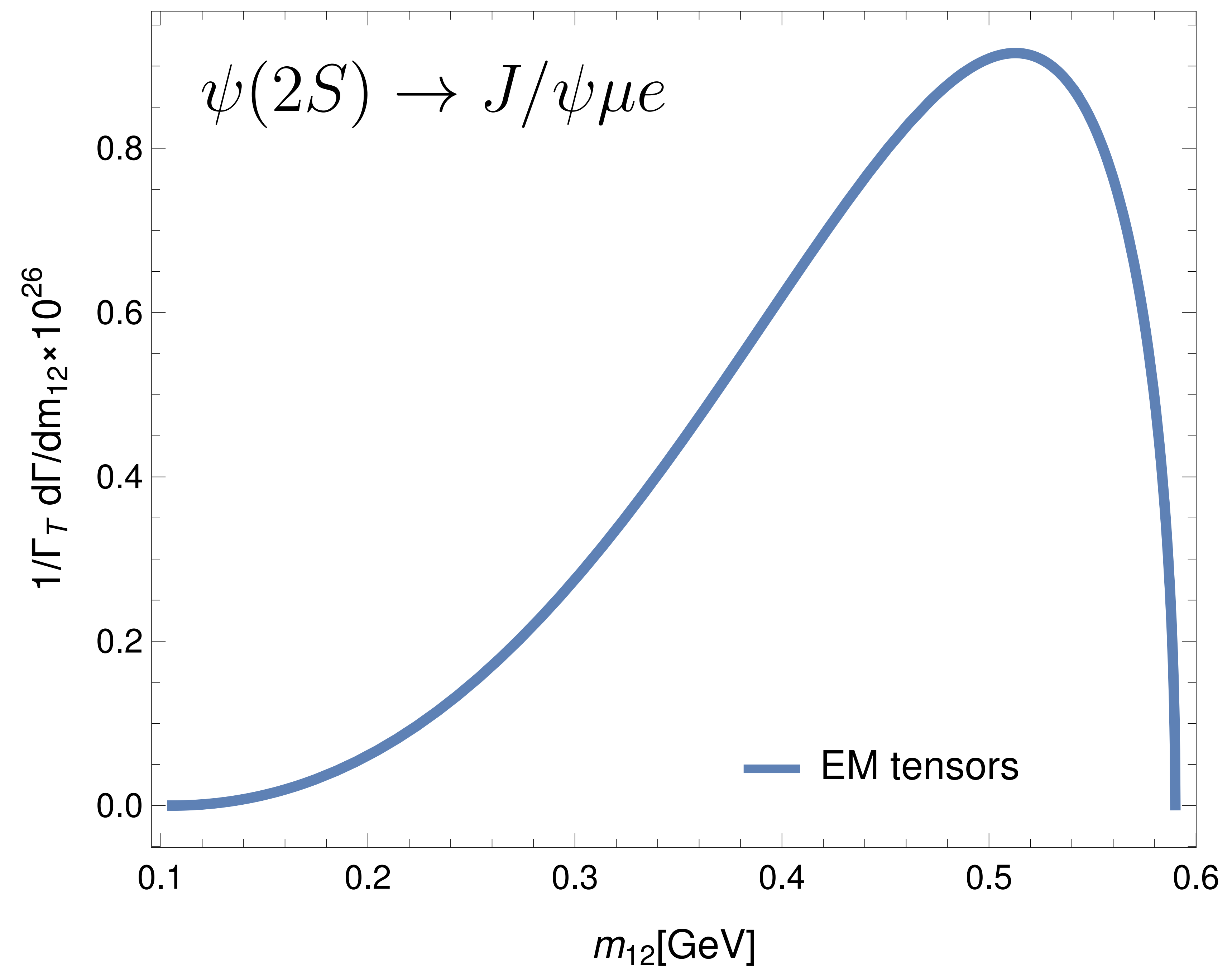
Differential decay rate $\frac{d\Gamma}{dm_{12}}$ with respect to the invariant dilepton mass $m_{12}^2 = (l_1 + l_2)^2$

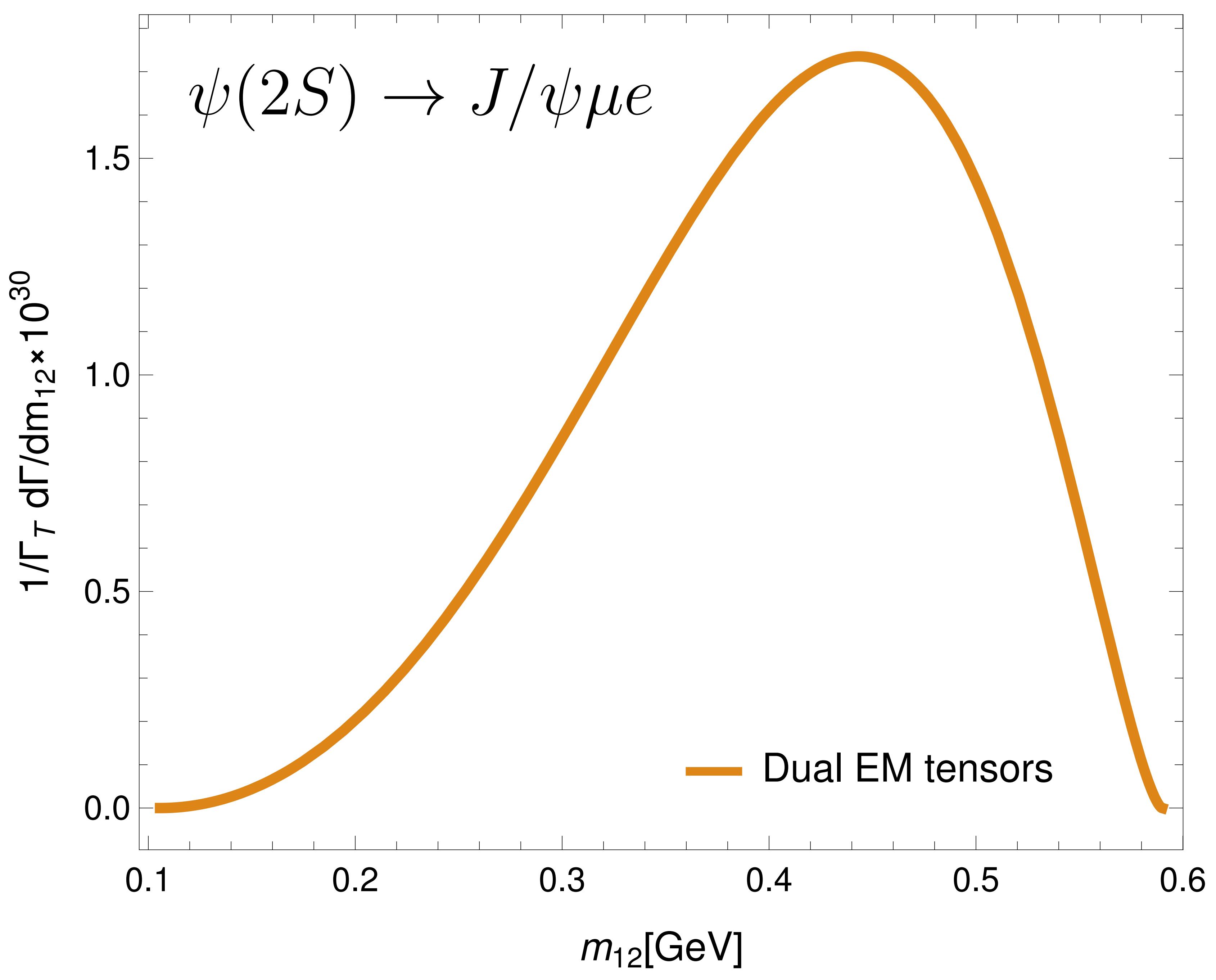




dim-7

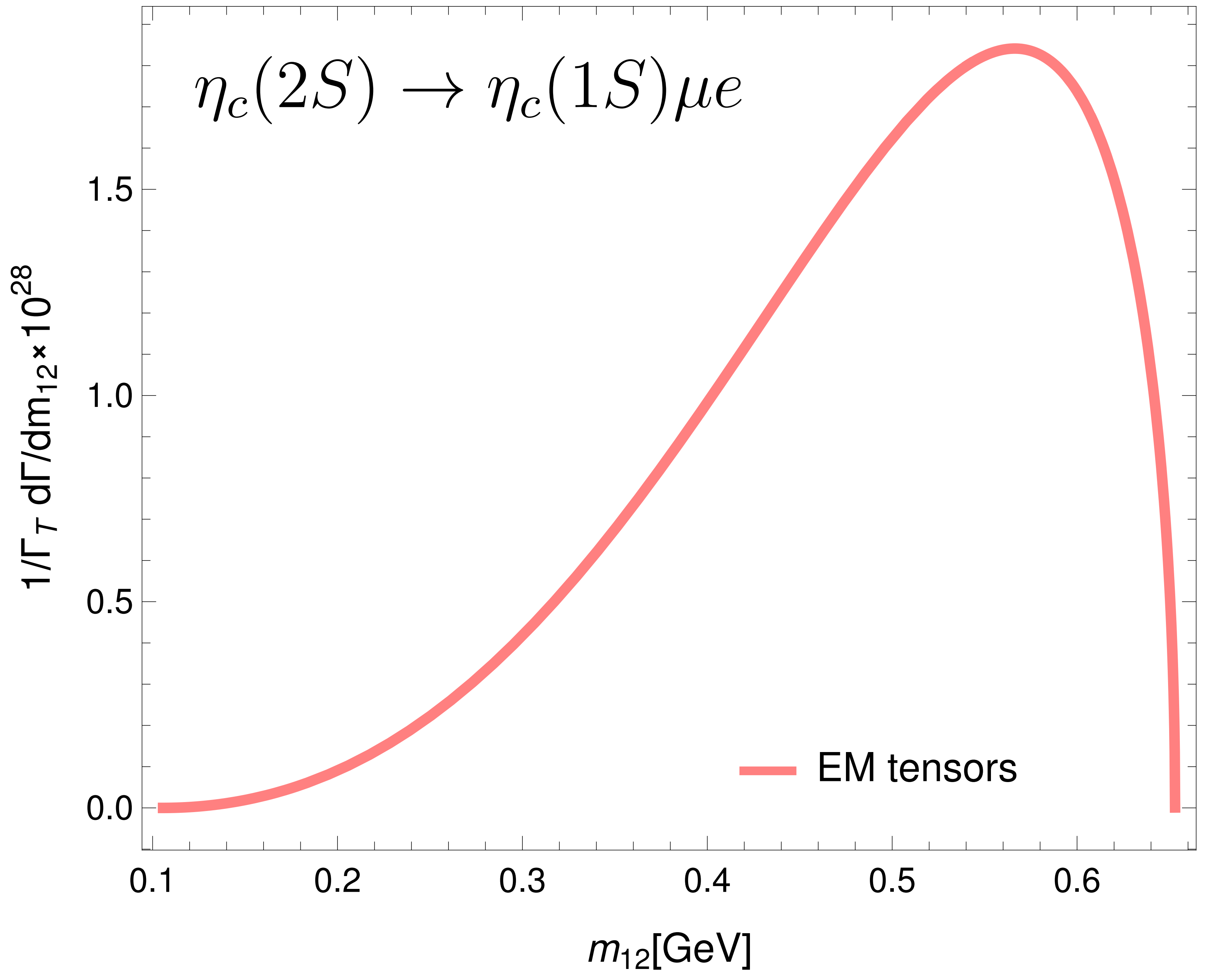
Differential decay rate $\frac{d\Gamma}{dm_{12}}$ with respect to the invariant dilepton mass $m_{12}^2 = (l_1 + l_2)^2$





dim-7

Differential decay rate $\frac{d\Gamma}{dm_{12}}$ with respect to the invariant dilepton mass $m_{12}^2 = (l_1 + l_2)^2$



Summary: Branching Ratios

$$\boxed{V' \to V\mu e}$$

Operator	$\mathrm{BR}(\Upsilon(2S) \to \Upsilon(1S)\mu e)$
Dim-5 dipolar	$[3.9 - 20.9] \times 10^{-31}$
Dim-7 EM	1.6×10^{-26}
Dim-7 Dual EM	5.0×10^{-31}
Operator	$\mathrm{BR}(\psi(2S) \to J/\psi\mu e)$
Dim-5 dipolar	$[3.2 - 25.0] \times 10^{-31}$
Dim-7 EM	2.1×10^{-27}
Dim-7 Dual EM	4.1×10^{-31}
Operator	$\mathrm{BR}(\rho' \to \rho\mu e)$
Dim-5 dipolar	$[1.7 - 77.8] \times 10^{-33}$
Dim-7 EM	1.7×10^{-32}
Dim-7 Dual EM	4.4×10^{-34}

	$\mathrm{BR}(J/\psi \to \mu e)$	$\mathrm{BR}(\Upsilon(1S) \to \mu e)$
Ref. [14] EFT model	$< 3 \times 10^{-24}$	$< 2 \times 10^{-24}$
Ref.[14] ISS	$< 9 \times 10^{-20}$	$< 2 \times 10^{-17}$
Ref. [24] new Z'	3.9×10^{-19}	$< 1.8 \times 10^{-16}$
Ref. [25] MRSSM	$\sim 10^{-24}$	$\sim 10^{-22}$
	$\mathrm{BR}(\psi(2S) \to \mu e)$	$\mathrm{BR}(\Upsilon(2S) \to \mu e)$
Ref. [24] new Z'	1×10^{-19}	$< 2.0 \times 10^{-16}$
Ref. [25] MRSSM	$\sim 10^{-25}$	$\sim 10^{-22}$

Similar results by comparing between $V' \to V\mu e$ (our results) and Vector Meson LFV annihilation processes $V \to \mu e$

Summary: Branching Ratios

$$\boxed{P' \to P\mu e}$$

Operator	$\mathrm{BR}(\eta_b(2S) \to \eta_b(1S)\mu e)$
Dim-7 EM	7.7×10^{-29}

Operator	$\mathrm{BR}(\eta_c(2S) \to \eta_c(1S)\mu e)$
Dim-7 EM	4.7×10^{-29}

Operator	Str. const.	Indirect upper limits on BR		
		$J/\psi \to \ell\ell'\gamma$	$\eta_c \to \ell\ell'$	$\chi_{c0}(1P) \to \ell\ell'$
$C^{S,RR}_{eu,\mu ecc}$	$\mu \to e$, Au	[1.5 - 1.4] $\times 10^{-21}$	[2.0 - 1.9] $\times 10^{-20}$	[3.4 - 3.2] $\times 10^{-19}$
$C^{S,RL}_{eu,\mu ecc}$	$\mu \to e$, Au	[1.5 - 1.4] $\times 10^{-21}$	[2.0 - 1.9] $\times 10^{-20}$	[3.4 - 3.2] $\times 10^{-19}$
$C^{S,RR}_{eu,\tau ecc}$	$\tau \to e\gamma$	[1.7 - 0.003] $\times 10^{-10}$	[6.8 - 0.01] $\times 10^{-9}$	[1.5 - 0.003] $\times 10^{-7}$
$C^{S,RL}_{eu,\tau ecc}$	$\tau \to e\gamma$	[2.0 - 0.09] $\times 10^{-10}$	[9.2 - 0.4] $\times 10^{-9}$	[1.3 - 0.08] $\times 10^{-7}$
$C^{S,RR}_{eu,\tau\mu cc}$	$\tau \to \mu\gamma$	[2.2 - 0.004] $\times 10^{-10}$	[8.7 - 0.02] $\times 10^{-9}$	[1.9 - 0.003] $\times 10^{-7}$
$C^{S,RL}_{eu,\tau\mu cc}$	$\tau \to \mu\gamma$	[2.6 - 0.1] $\times 10^{-10}$	[1.2 - 0.05] $\times 10^{-8}$	[1.7 - 0.1] $\times 10^{-7}$

(b) Scalar operators. We find similar limits for $\psi(2S) \to \ell\ell'\gamma$, about a factor of 4 (2) stronger for the μe ($\tau\ell$) channels. See text for details on how the indirect upper limits have been estimated.

[22] L. Calibbi, T. Li, X. Marcano, and M. A. Schmidt, Phys. Rev. D 106, 115039 (2022), arXiv:2207.10913

Conclusions

- Possibility to distinguish the energy behavior between dim-5 and dim-7.
- For the dim-5 operator, dominant contribution comes from the dipolar magnetic interaction, with 2 orders of magnitude above the quadrupolar electric interaction.
- For the dim-7 operator, EM part is one order of magnitude greater than the dual EM part, opposite to previous results obtained with nuclei interactions.
  (arXiv:2305.04974, Fabiola Fortuna, Xabier Marcano, Marcela Martín and Pablo Roig)
- Although quarkonia improves BR's (because of smaller decay widths), results are still very suppressed, regardless of quark content.
- Similar branching ratios from direct LFV decays of quarkonia
- Finding any evidence of LFV de-excitation at larger BRs would imply the existence of a new LFV mechanism not captured by our effective approach
- Dilepton invariant mass may be useful to distinguish our effective model from nuclei models.

Thank you!

Backup Slides

Coupling values

Coupling	Value
$g_{\rho'}$	12.918
g_{ρ}	4.962
$g_{\psi(2S)}$	18.799
$g_{J/\psi}$	11.219
$g_{\Upsilon(2S)}$	61.610
$g_{\Upsilon(1S)}$	40.435

Coupling	Value (GeV^{-1})
$g_{\rho'\pi\gamma}$	0.063
$g_{\rho\pi\gamma}$	0.206
$g_{\psi(2S)\eta_c(1S)\gamma}$	−0.044
$g_{J/\psi\,\eta_c(1S)\gamma}$	0.264
$g_{J/\psi\,\eta_c(2S)\gamma}$	−0.007
$g_{\Upsilon(2S)\eta_b(1S)\gamma}$	0.003
$g_{\Upsilon(1S)\eta_b(1S)\gamma}$	−0.043
$g_{\Upsilon(1S)\eta_b(2S)\gamma}$	0.002

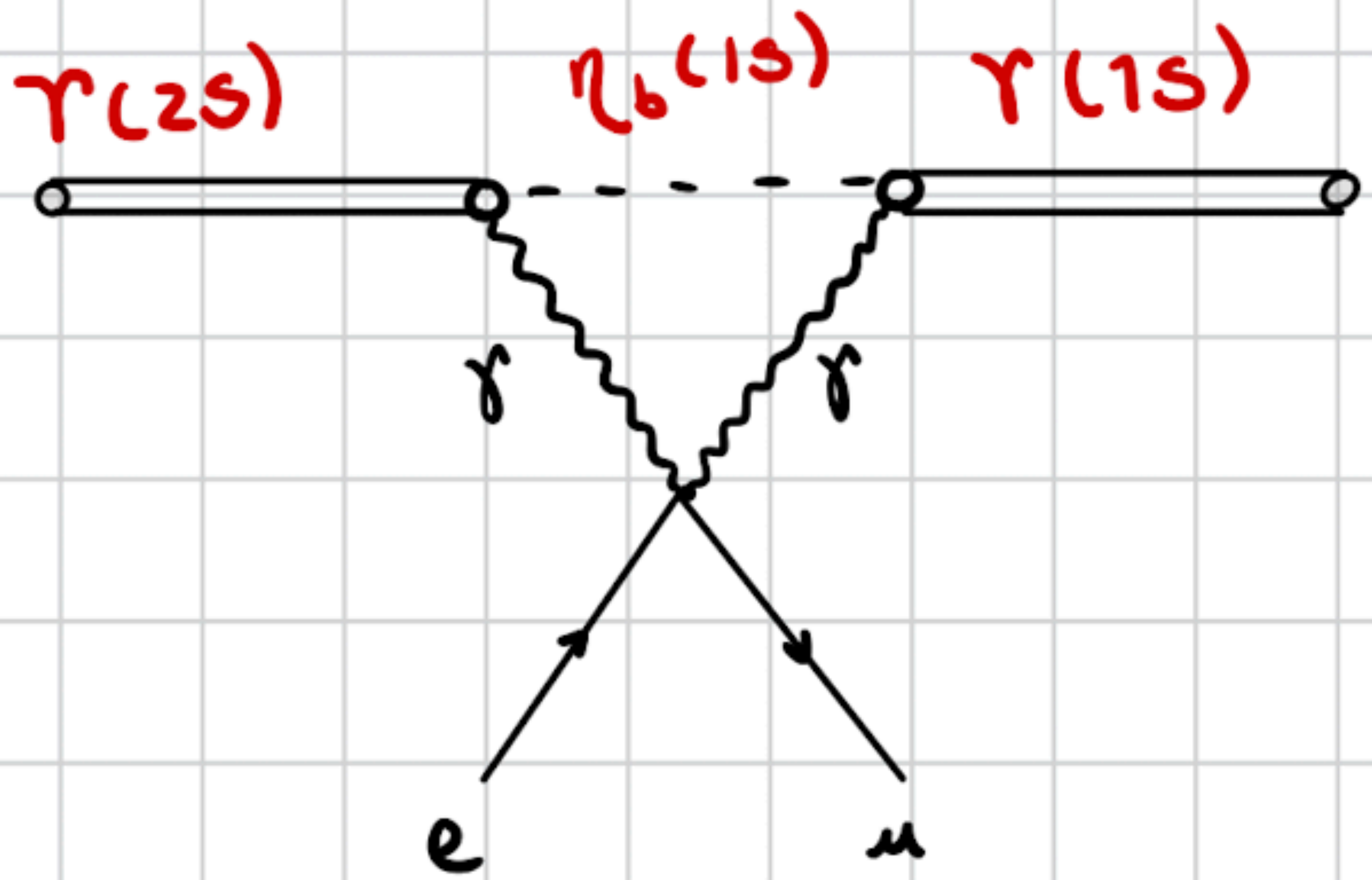
Some values are obtained using VMD effective theory, while others are taken from M. Ridwan arXiv:2409.13172 and M. Li arXiv:1803.11519

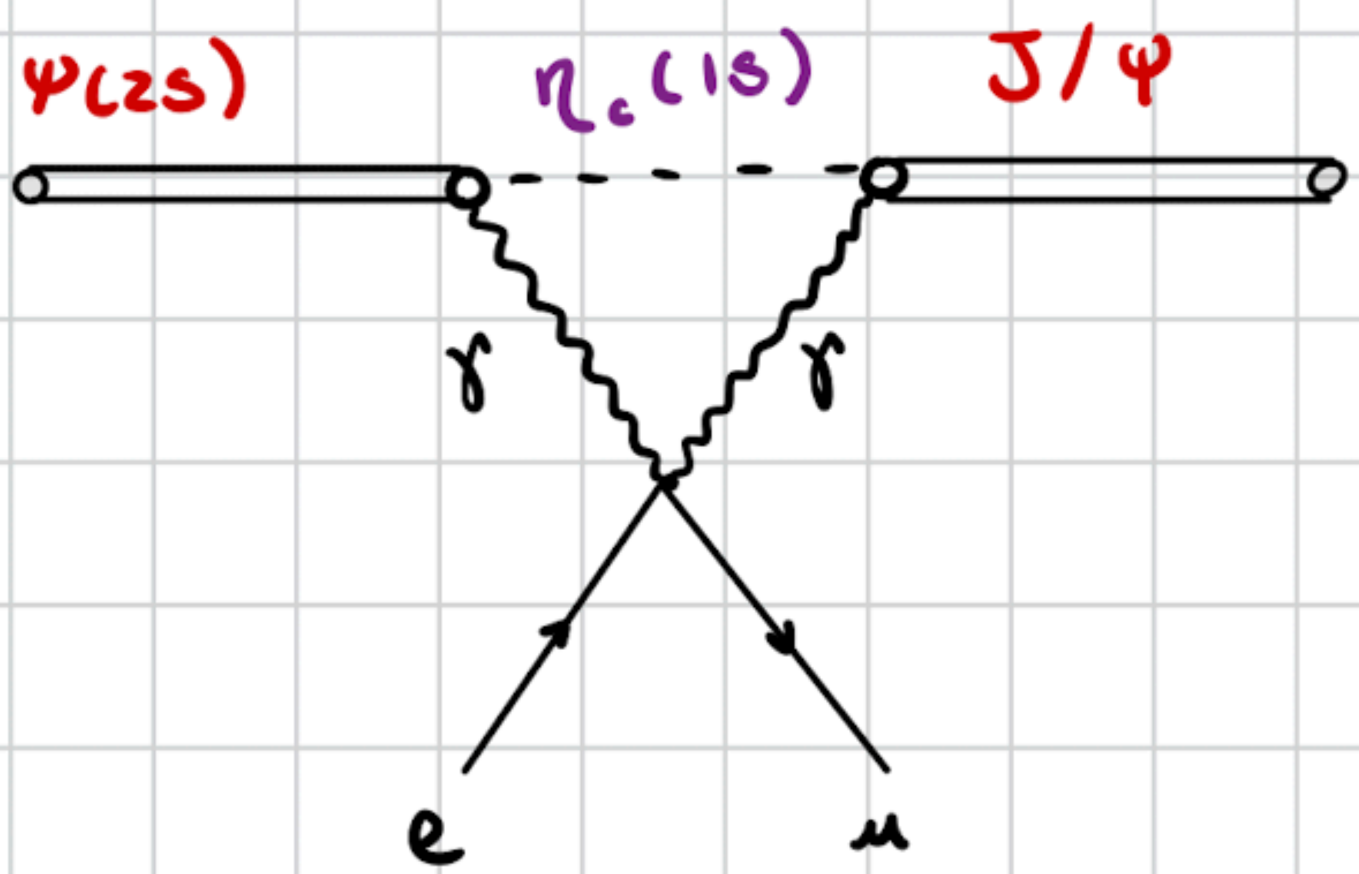
Quarkonia

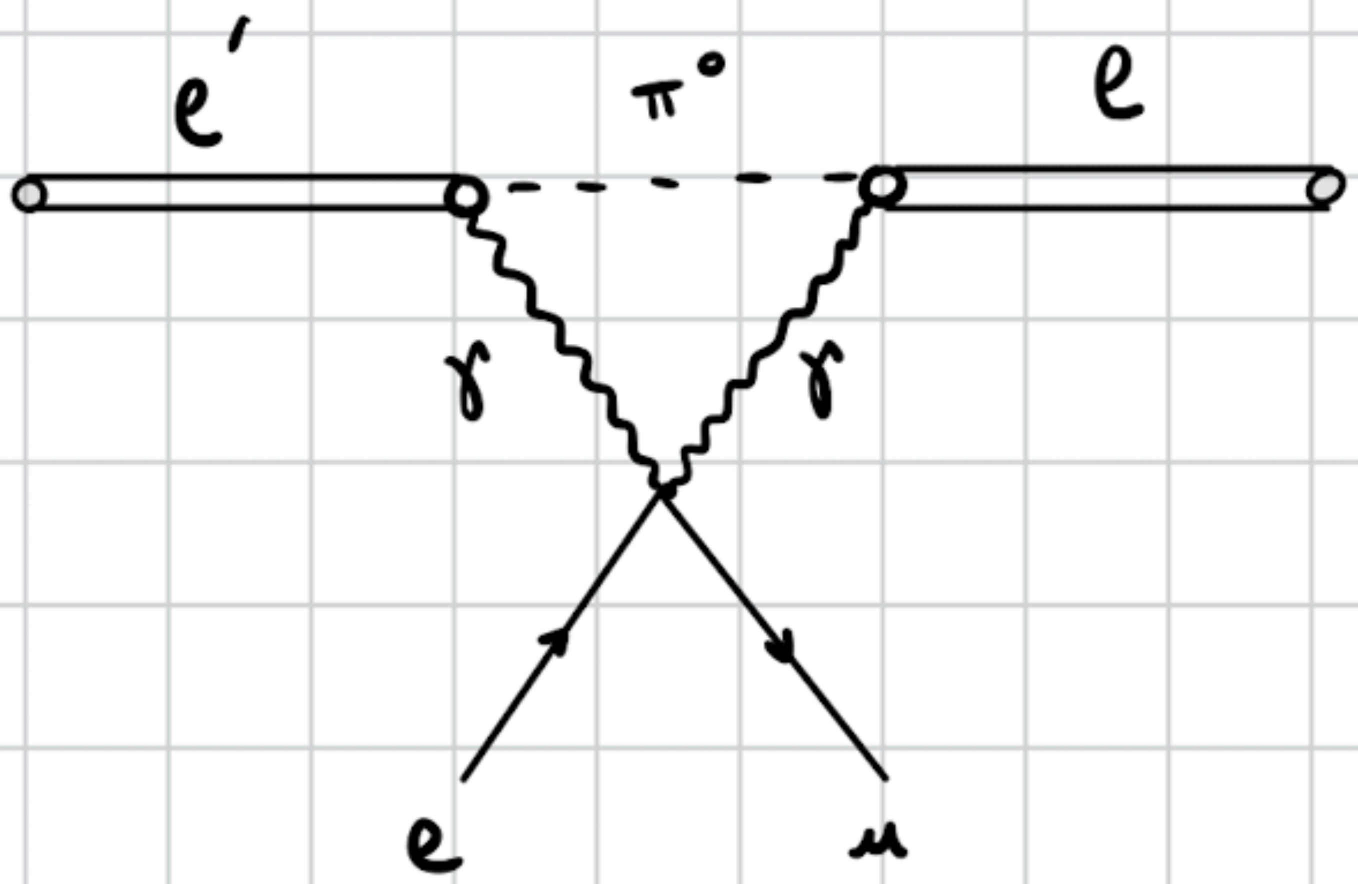
	$I^G(J^{PC})$	m (GeV)	Γ
π	$1^-(0^{-+})$	0.134	~ 0
ρ	$1^+(1^{--})$	0.77	149.1 MeV
ρ'	$1^+(1^{--})$	1.46	400 MeV
$\Upsilon(2S)$	$0^-(1^{--})$	10.02	31.98 KeV
$\Upsilon(1S)$	$0^-(1^{--})$	9.46	54.02 KeV
$\eta_b(1S)$	$0^+(0^{-+})$	9.39	10 MeV
$\Psi(2S)$	$0^-(1^{--})$	3.68	299 KeV
$\Psi(1S) = J/\Psi$	$0^-(1^{--})$	3.09	92.9 KeV
$\eta_c(2S)$	$0^+(0^{-+})$	3.63	11.3 MeV
$\eta_c(1S)$	$0^+(0^{-+})$	2.98	32 MeV

Bottomonia ($b\bar{b}$)

Charmonia ($c\bar{c}$)







Pseudoscalar (P′ ⟶ Peμ)