Lepton flavor violating meson decays

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D. E. Hazard and A. A. Petrov, Phys. Rev. D. 94, 074023 (2016)

Outline

- Introduction
  - Motivation
  - Effective Lagrangian
- Two-body meson decays
  - Vector
  - Pseudoscalar
  - Scalar
- Three-body vector quarkonium decays
  - Resonant transitions
  - Nonresonant transitions
- Summary

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- ***Single operator dominance:*** The assumption that only one effective operator dictates the result.
- Model independence: Any NP scenario involving LFV can be matched to $L_{eff.}$

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  - Scalar: χ_{b0}(bb), χ_{c0}(cc), and excited states
- Calculate mesons to $\tau\,\mu$, $\tau\,e$, $\mu\,e$

Effective Lagrangian

$$\mathcal{L}_{\rm eff} = \mathcal{L}_D + \mathcal{L}_{\ell q} + \mathcal{L}_G + \ldots \; ^*$$

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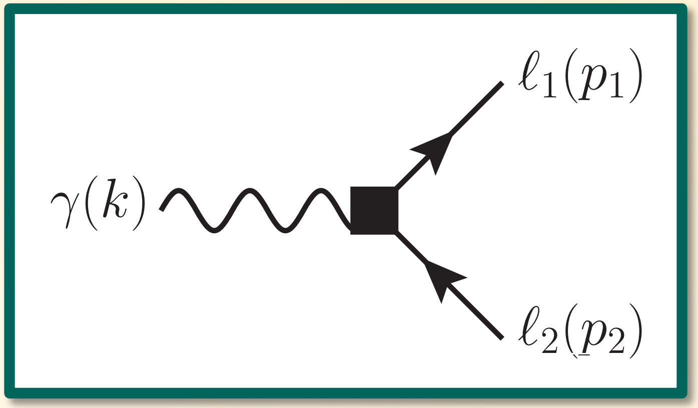

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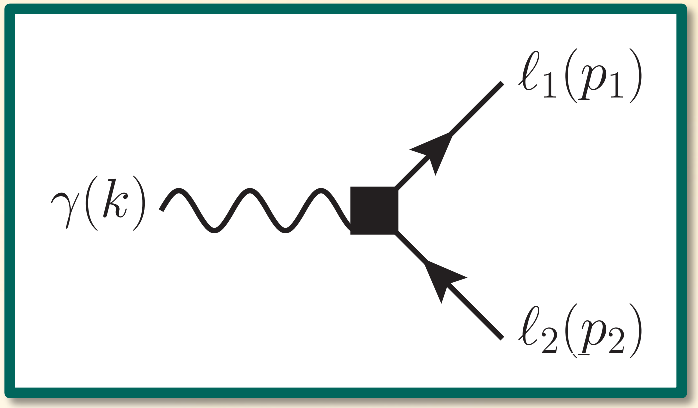

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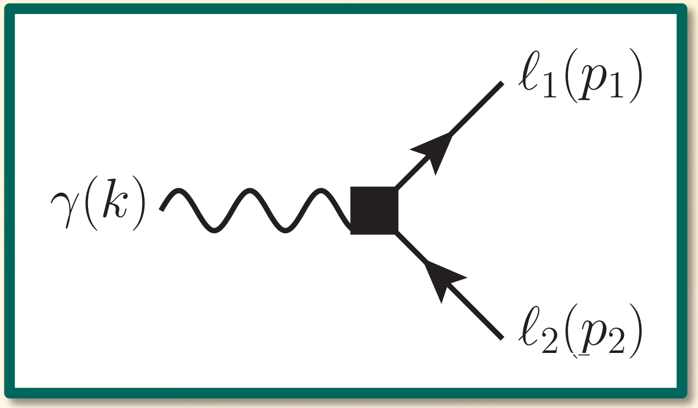

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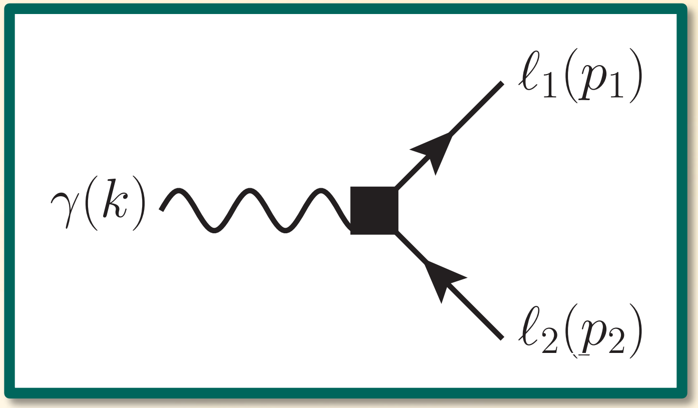

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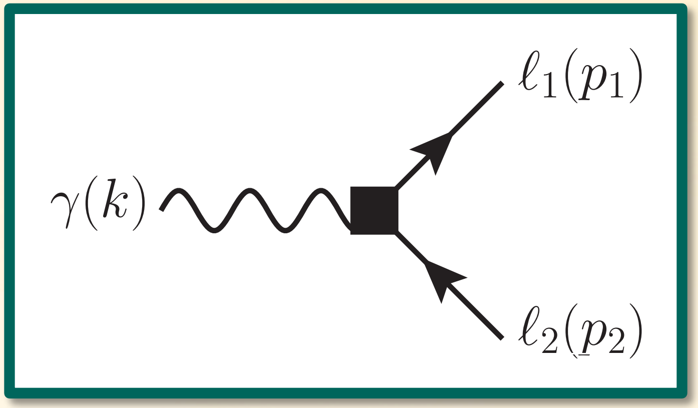
$P_{R(L)} = (1 \pm \gamma^5)/2$



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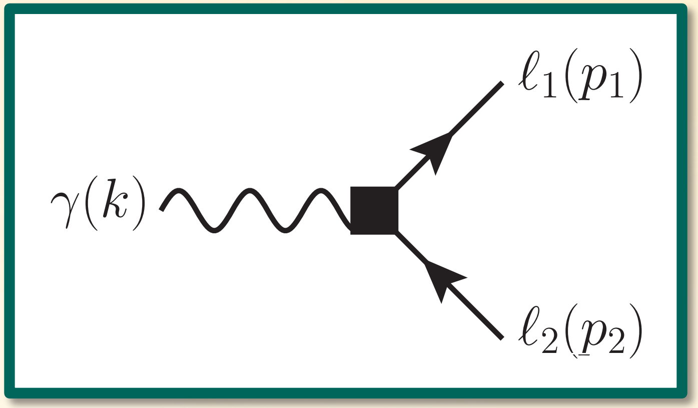
Dipole operators are selected by the quantum numbers of the 2-body vector quarkonium decays.



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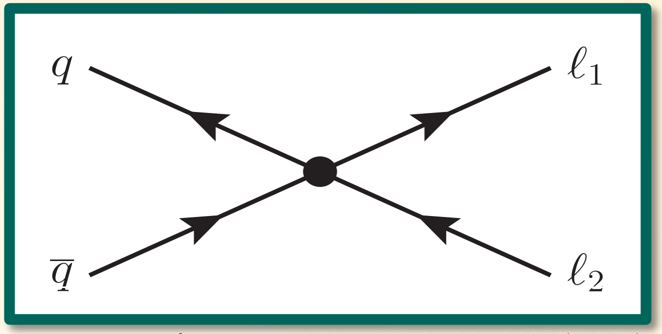

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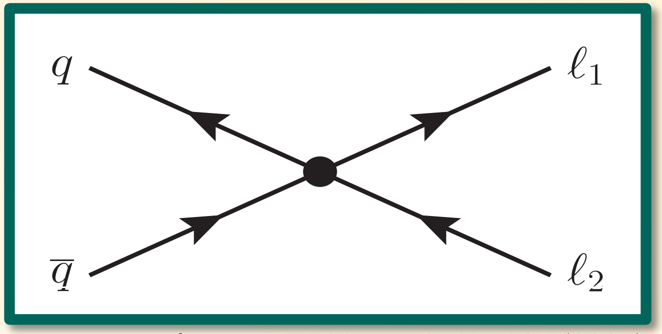
Vector Wilson coefficients



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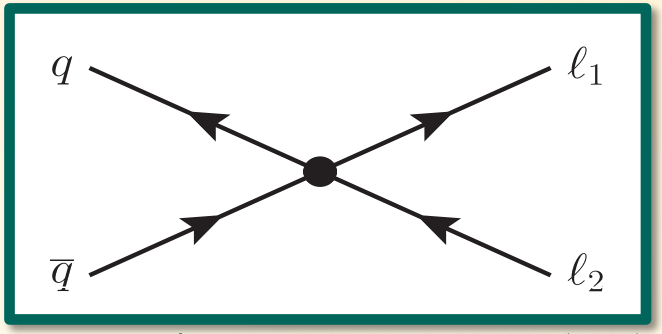
Axial Wilson coefficients



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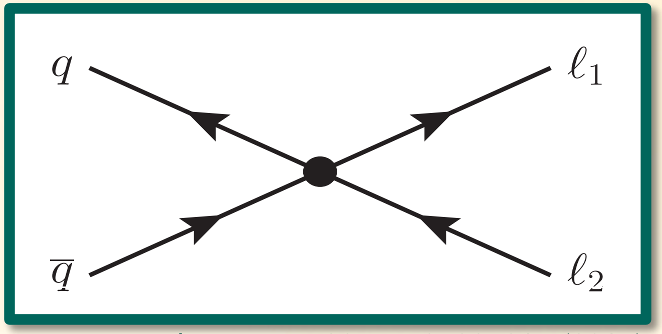
Scalar Wilson coefficients



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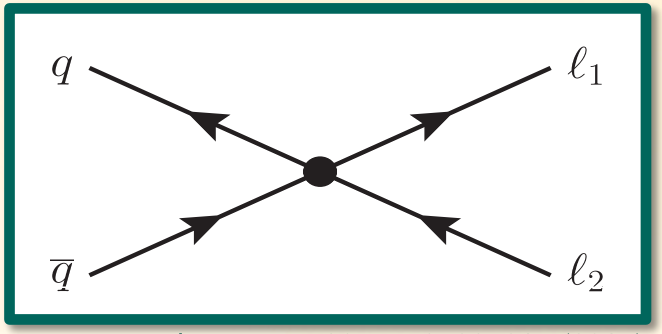
Pseudoscalar Wilson coefficients



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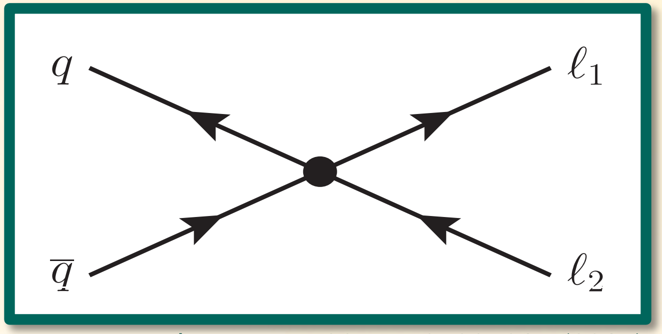
Tensor Wilson coefficients



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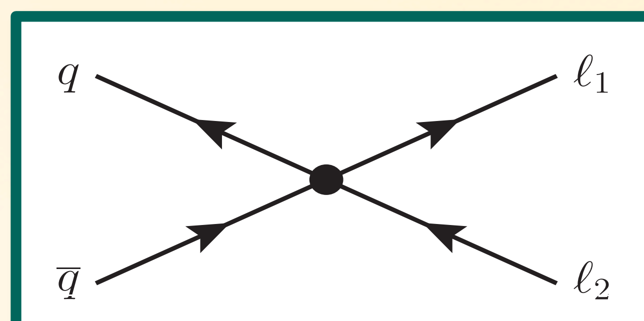
$$+ m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2} \bar{\ell}_1 P_L \ell_2 + C_{SL}^{q\ell_1\ell_2} \bar{\ell}_1 P_R \ell_2 \right) \bar{q} q$$

$$+ m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2} \bar{\ell}_1 P_L \ell_2 + C_{PL}^{q\ell_1\ell_2} \bar{\ell}_1 P_R \ell_2 \right) \bar{q}\gamma_5 q$$

$$+ m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2} \bar{\ell}_1 \sigma^{\mu\nu} P_L \ell_2 + C_{TL}^{q\ell_1\ell_2} \bar{\ell}_1 \sigma^{\mu\nu} P_R \ell_2 \right) \bar{q}\sigma_{\mu\nu} q + h.c. \Big]^*$$

m_q = MS bar quark mass



*A. Celis, V. Cirigliano and E. Passemar, Phys. Rev. D 89, no. 9, 095014 (2014)

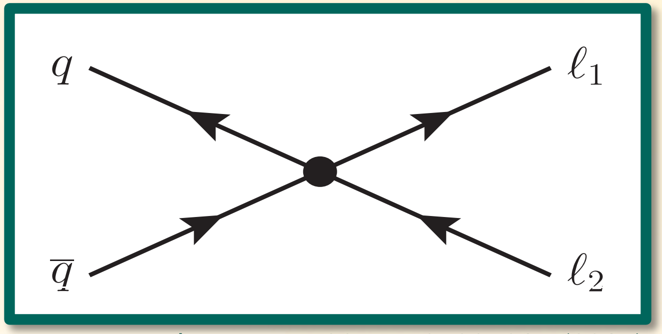
Effective Lagrangian

Four fermion Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\ell q} \;=\; -\frac{1}{\Lambda^2}\sum_q \Big[& \left(C^{q\ell_1\ell_2}_{VR}\,\overline{\ell}_1\gamma^\mu P_R \ell_2 + C^{q\ell_1\ell_2}_{VL}\,\overline{\ell}_1\gamma^\mu P_L \ell_2\right)\overline{q}\gamma_\mu q \\
& + \left(C^{q\ell_1\ell_2}_{AR}\,\overline{\ell}_1\gamma^\mu P_R \ell_2 + C^{q\ell_1\ell_2}_{AL}\,\overline{\ell}_1\gamma^\mu P_L \ell_2\right)\overline{q}\gamma_\mu\gamma_5 q \\
& + m_2 m_q G_F \left(C^{q\ell_1\ell_2}_{SR}\,\overline{\ell}_1 P_L \ell_2 + C^{q\ell_1\ell_2}_{SL}\,\overline{\ell}_1 P_R \ell_2\right)\overline{q}q \\
& + m_2 m_q G_F \left(C^{q\ell_1\ell_2}_{PR}\,\overline{\ell}_1 P_L \ell_2 + C^{q\ell_1\ell_2}_{PL}\,\overline{\ell}_1 P_R \ell_2\right)\overline{q}\gamma_5 q \\
& + m_2 m_q G_F \left(C^{q\ell_1\ell_2}_{TR}\,\overline{\ell}_1 \sigma^{\mu\nu} P_L \ell_2 + C^{q\ell_1\ell_2}_{TL}\,\overline{\ell}_1 \sigma^{\mu\nu} P_R \ell_2\right)\overline{q}\sigma_{\mu\nu} q + h.c. \Big]
\end{aligned}
$$

m_q = MS bar quark mass

G_F = Fermi constant



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Effective Lagrangian

Four fermion Lagrangian

$$\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2}\sum_q \Big[\left(C_{VR}^{q\ell_1\ell_2}\bar{\ell}_1\gamma^\mu P_R \ell_2 + C_{VL}^{q\ell_1\ell_2}\bar{\ell}_1\gamma^\mu P_L \ell_2\right)\bar{q}\gamma_\mu q$$

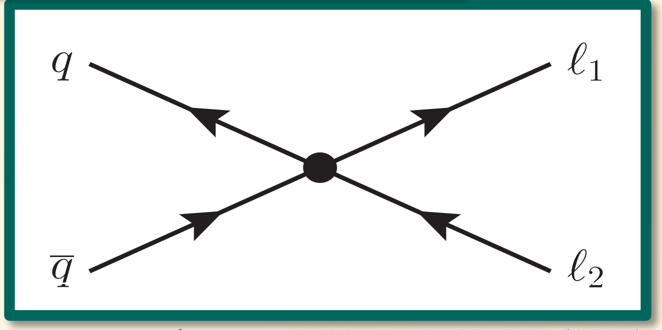
$$+ \left(C_{AR}^{q\ell_1\ell_2}\bar{\ell}_1\gamma^\mu P_R \ell_2 + C_{AL}^{q\ell_1\ell_2}\bar{\ell}_1\gamma^\mu P_L \ell_2\right)\bar{q}\gamma_\mu\gamma_5 q$$

$$+ m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2}\bar{\ell}_1 P_L \ell_2 + C_{SL}^{q\ell_1\ell_2}\bar{\ell}_1 P_R \ell_2\right)\bar{q}q$$

$$+ m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2}\bar{\ell}_1 P_L \ell_2 + C_{PL}^{q\ell_1\ell_2}\bar{\ell}_1 P_R \ell_2\right)\bar{q}\gamma_5 q$$

$$+ m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2}\bar{\ell}_1 \sigma^{\mu\nu} P_L \ell_2 + C_{TL}^{q\ell_1\ell_2}\bar{\ell}_1 \sigma^{\mu\nu} P_R \ell_2\right)\bar{q}\sigma_{\mu\nu} q + h.c. \Big]^*$$

Vector and tensor operators are selected by the quantum numbers of the 2-body vector quarkonium decays.



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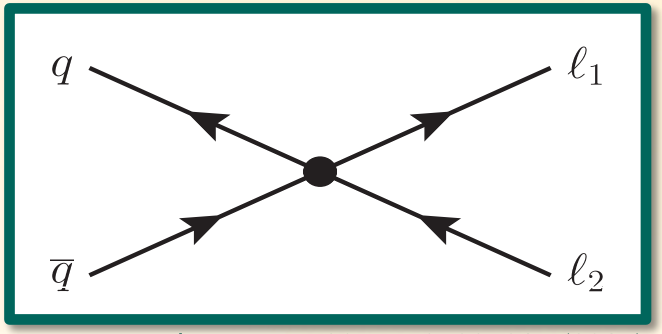
Effective Lagrangian

Four fermion Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\ell q} \;=\; -\frac{1}{\Lambda^2}\sum_q \Big[& \left(C_{VR}^{q\ell_1\ell_2}\bar{\ell}_1\gamma^\mu P_R\ell_2 + C_{VL}^{q\ell_1\ell_2}\bar{\ell}_1\gamma^\mu P_L\ell_2\right)\bar{q}\gamma_\mu q \\
& + \left(C_{AR}^{q\ell_1\ell_2}\bar{\ell}_1\gamma^\mu P_R\ell_2 + C_{AL}^{q\ell_1\ell_2}\bar{\ell}_1\gamma^\mu P_L\ell_2\right)\bar{q}\gamma_\mu\gamma_5 q \\
& + m_2 m_q G_F\left(C_{SR}^{q\ell_1\ell_2}\bar{\ell}_1 P_L\ell_2 + C_{SL}^{q\ell_1\ell_2}\bar{\ell}_1 P_R\ell_2\right)\bar{q}q \\
& + m_2 m_q G_F\left(C_{PR}^{q\ell_1\ell_2}\bar{\ell}_1 P_L\ell_2 + C_{PL}^{q\ell_1\ell_2}\bar{\ell}_1 P_R\ell_2\right)\bar{q}\gamma_5 q \\
& + m_2 m_q G_F\left(C_{TR}^{q\ell_1\ell_2}\bar{\ell}_1\sigma^{\mu\nu} P_L\ell_2 + C_{TL}^{q\ell_1\ell_2}\bar{\ell}_1\sigma^{\mu\nu} P_R\ell_2\right)\bar{q}\sigma_{\mu\nu} q + h.c. \Big]^{*}
\end{aligned}
$$

Axial and pseudoscalar operators are selected by the quantum numbers of the 2-body pseudoscalar meson decays.



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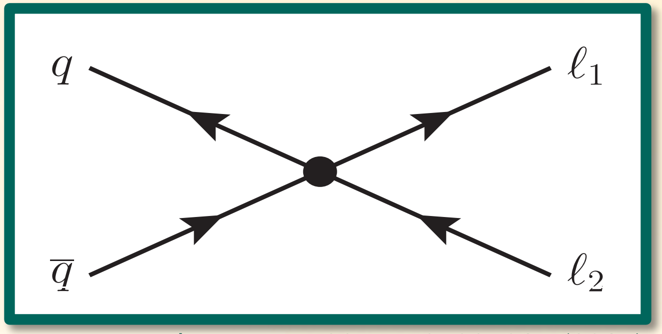
Effective Lagrangian

Four fermion Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\ell q} \;=\; -\frac{1}{\Lambda^2}\sum_q \Big[& \left(C_{VR}^{q\ell_1\ell_2}\,\overline{\ell}_1\gamma^\mu P_R\ell_2 + C_{VL}^{q\ell_1\ell_2}\,\overline{\ell}_1\gamma^\mu P_L\ell_2 \right) \overline{q}\gamma_\mu q \\
& + \left(C_{AR}^{q\ell_1\ell_2}\,\overline{\ell}_1\gamma^\mu P_R\ell_2 + C_{AL}^{q\ell_1\ell_2}\,\overline{\ell}_1\gamma^\mu P_L\ell_2 \right) \overline{q}\gamma_\mu\gamma_5 q \\
& + m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2}\,\overline{\ell}_1 P_L\ell_2 + C_{SL}^{q\ell_1\ell_2}\,\overline{\ell}_1 P_R\ell_2 \right) \overline{q}q \\
& + m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2}\,\overline{\ell}_1 P_L\ell_2 + C_{PL}^{q\ell_1\ell_2}\,\overline{\ell}_1 P_R\ell_2 \right) \overline{q}\gamma_5 q \\
& + m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2}\,\overline{\ell}_1\sigma^{\mu\nu} P_L\ell_2 + C_{TL}^{q\ell_1\ell_2}\,\overline{\ell}_1\sigma^{\mu\nu} P_R\ell_2 \right) \overline{q}\sigma_{\mu\nu} q + h.c. \Big]^*
\end{aligned}
$$

Scalar operators are selected by the quantum numbers of the 2-body scalar quarkonium decays.



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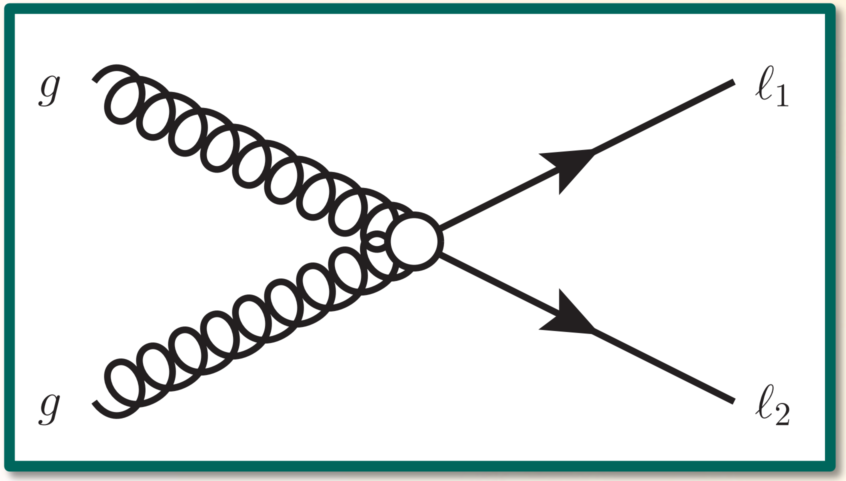
Effective Lagrangian

Gluonic Lagrangian

$$\mathcal{L}_G = -\frac{m_2 G_F}{\Lambda^2}\frac{\beta_L}{4\alpha_s}\Big[\left(C^{\ell_1\ell_2}_{GR}\bar{\ell}_1 P_L \ell_2 + C^{\ell_1\ell_2}_{GL}\bar{\ell}_1 P_R \ell_2\right) G^a_{\mu\nu}G^{a\mu\nu} + \left(C^{\ell_1\ell_2}_{\tilde{G}R}\bar{\ell}_1 P_L \ell_2 + C^{\ell_1\ell_2}_{\tilde{G}L}\bar{\ell}_1 P_R \ell_2\right) G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} + h.c.\Big]^*$$



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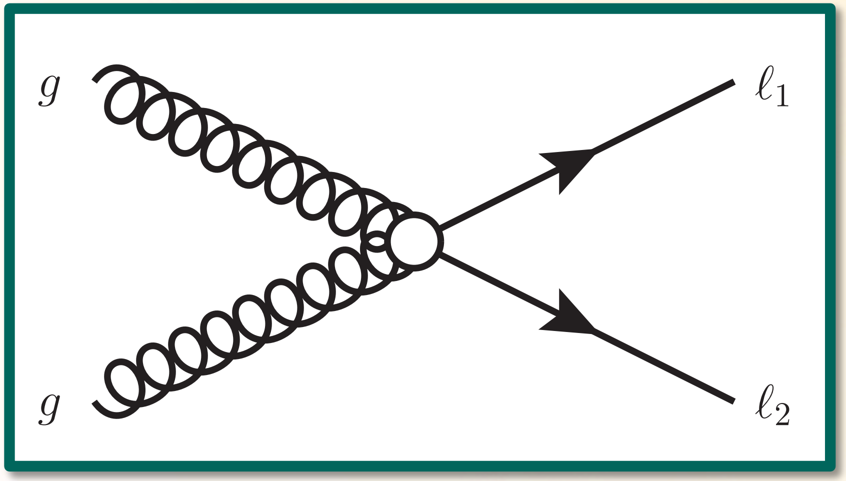
Effective Lagrangian

Gluonic Lagrangian

$$\mathcal{L}_G = -\frac{m_2 G_F}{\Lambda^2}\frac{\beta_L}{4\alpha_s}\Big[\left(C_{GR}^{\ell_1\ell_2}\bar{\ell}_1 P_L \ell_2 + C_{GL}^{\ell_1\ell_2}\bar{\ell}_1 P_R \ell_2\right) G^a_{\mu\nu}G^{a\mu\nu} + \left(C_{\tilde{G}R}^{\ell_1\ell_2}\bar{\ell}_1 P_L \ell_2 + C_{\tilde{G}L}^{\ell_1\ell_2}\bar{\ell}_1 P_R \ell_2\right) G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} + h.c.\Big]^*$$



1 loop beta function defined for the number of light active flavors, L, relevant to the scale of the process (μ=2GeV).

$\beta_L = -9\alpha_s^2/(2\pi)$

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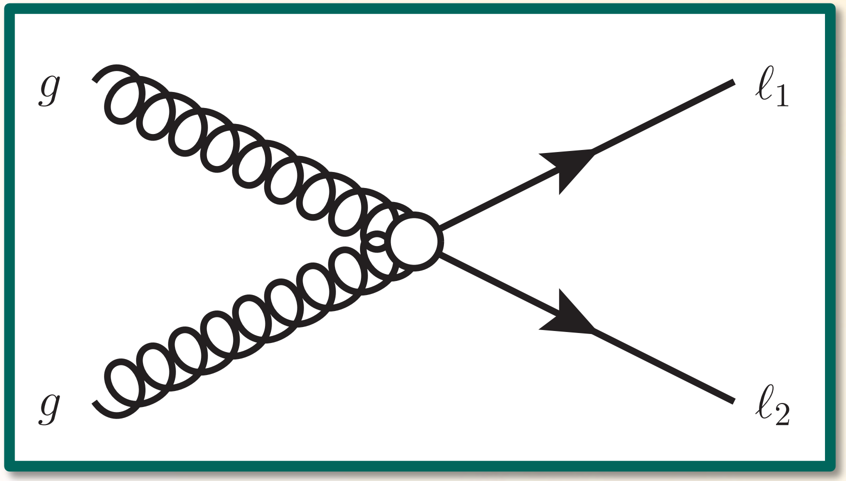
Effective Lagrangian

Gluonic Lagrangian

$$\mathcal{L}_G = -\frac{m_2 G_F}{\Lambda^2}\frac{\beta_L}{4\alpha_s}\Big[\left(C^{\ell_1\ell_2}_{GR}\bar{\ell}_1 P_L \ell_2 + C^{\ell_1\ell_2}_{GL}\bar{\ell}_1 P_R \ell_2\right) G^a_{\mu\nu}G^{a\mu\nu} + \left(C^{\ell_1\ell_2}_{\tilde{G}R}\bar{\ell}_1 P_L \ell_2 + C^{\ell_1\ell_2}_{\tilde{G}L}\bar{\ell}_1 P_R \ell_2\right) G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} + h.c.\Big]^*$$



α_s = QCD coupling constant

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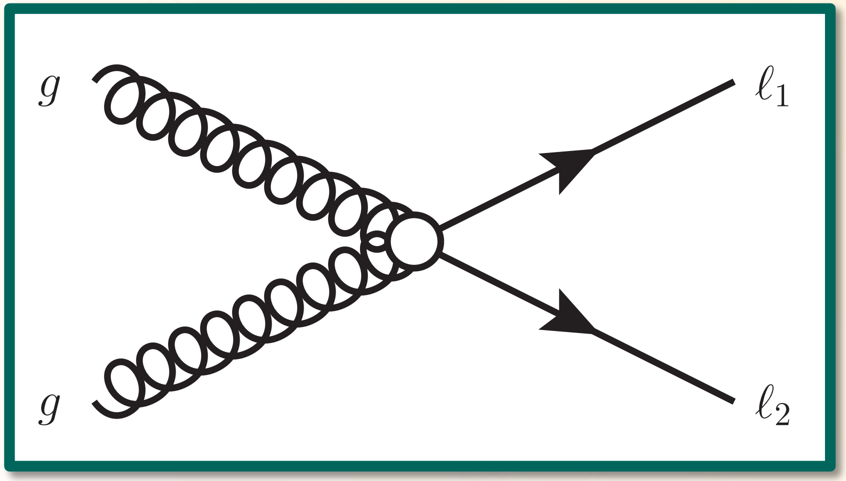
Effective Lagrangian

Gluonic Lagrangian

$$\mathcal{L}_G = -\frac{m_2 G_F}{\Lambda^2}\frac{\beta_L}{4\alpha_s}\Big[\Big(C_{GR}^{\ell_1\ell_2}\bar{\ell}_1 P_L \ell_2 + C_{GL}^{\ell_1\ell_2}\bar{\ell}_1 P_R \ell_2\Big) G^a_{\mu\nu}G^{a\mu\nu} + \Big(C_{\tilde{G}R}^{\ell_1\ell_2}\bar{\ell}_1 P_L \ell_2 + C_{\tilde{G}L}^{\ell_1\ell_2}\bar{\ell}_1 P_R \ell_2\Big) G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} + h.c.\Big]^*$$



Gluonic Wilson coefficients

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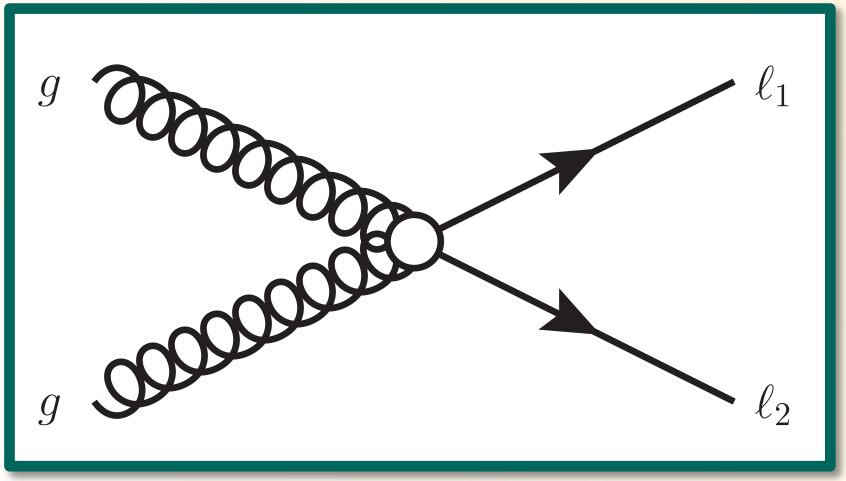
Effective Lagrangian

Gluonic Lagrangian

$$\mathcal{L}_G = -\frac{m_2 G_F}{\Lambda^2}\frac{\beta_L}{4\alpha_s}\Big[\left(C_{GR}^{\ell_1\ell_2}\bar{\ell}_1 P_L \ell_2 + C_{GL}^{\ell_1\ell_2}\bar{\ell}_1 P_R \ell_2\right) G^a_{\mu\nu}G^{a\mu\nu}$$

$$+ \left(C_{\tilde{G}R}^{\ell_1\ell_2}\bar{\ell}_1 P_L \ell_2 + C_{\tilde{G}L}^{\ell_1\ell_2}\bar{\ell}_1 P_R \ell_2\right) G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} + h.c.\ \Big]^*$$



Gluonic operators selected by the 2-body scalar quarkonium decays.

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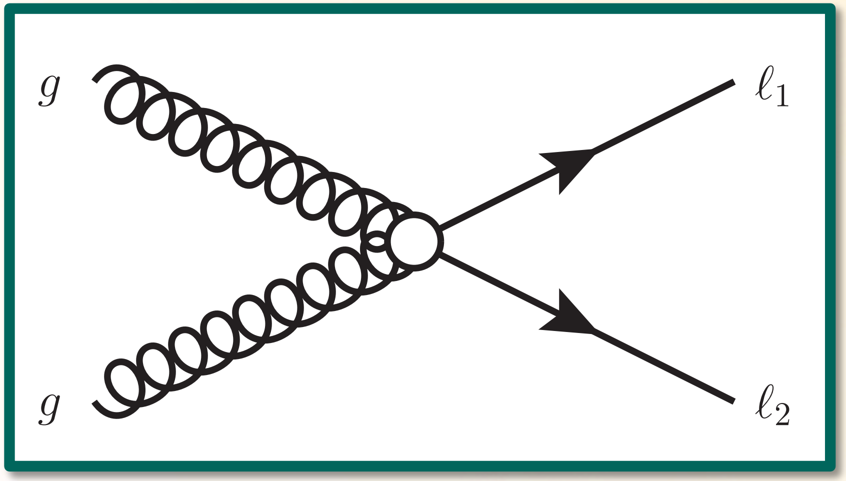
Effective Lagrangian

Gluonic Lagrangian

$$\mathcal{L}_G = -\frac{m_2 G_F}{\Lambda^2}\frac{\beta_L}{4\alpha_s}\Big[\left(C^{\ell_1\ell_2}_{GR}\,\overline{\ell}_1 P_L \ell_2 + C^{\ell_1\ell_2}_{GL}\,\overline{\ell}_1 P_R \ell_2\right) G^a_{\mu\nu} G^{a\mu\nu} + \left(C^{\ell_1\ell_2}_{\tilde{G}R}\,\overline{\ell}_1 P_L \ell_2 + C^{\ell_1\ell_2}_{\tilde{G}L}\,\overline{\ell}_1 P_R \ell_2\right) G^a_{\mu\nu} \widetilde{G}^{a\mu\nu} + h.c.\Big]^*$$



Gluonic operators selected by the 2-body pseudoscalar quarkonium decays.

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2-body vector quarkonium decays

$$\langle 0|\bar{q}\gamma^\mu q|V(p)\rangle = f_V m_V \epsilon^\mu(p)\,,$$

Decay constant

$$\langle 0|\bar{q}\sigma^{\mu\nu} q|V(p)\rangle = i f_V^T \left(\epsilon^\mu p^\nu - p^\mu \epsilon^\nu\right)$$

Tensor decay constant

2-body vector quarkonium decays

$$\langle 0|\overline{q}\gamma^{\mu}q|V(p)\rangle \;=\; f_V m_V \epsilon^{\mu}(p)\,,$$

Decay constant

$$\langle 0|\overline{q}\sigma^{\mu\nu}q|V(p)\rangle \;=\; i f_V^T\left(\epsilon^{\mu}p^{\nu} - p^{\mu}\epsilon^{\nu}\right)$$

Tensor decay constant

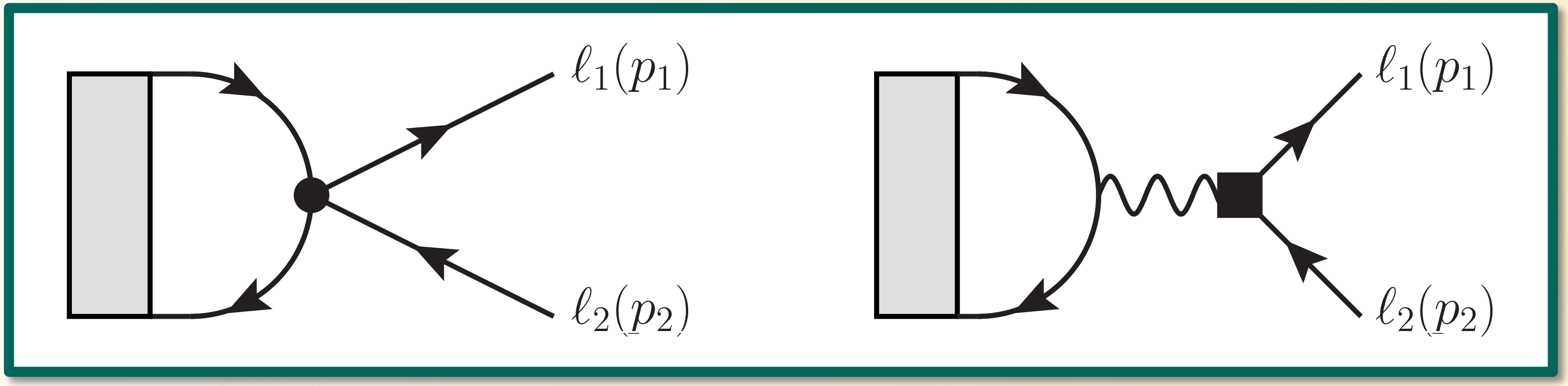
V = any quarkonium with quantum numbers 1^{--} i.e. Υ, J/ψ, Φ, ρ, ω

2-body vector quarkonium decays

$$\langle 0|\bar{q}\gamma^\mu q|V(p)\rangle = f_V m_V \epsilon^\mu(p)\,,$$ Decay constant

$$\langle 0|\bar{q}\sigma^{\mu\nu} q|V(p)\rangle = i f_V^T \left(\epsilon^\mu p^\nu - p^\mu \epsilon^\nu\right)$$ Tensor decay constant

V = any quarkonium with quantum numbers 1^{--} i.e. Υ, J/ψ, Φ, ρ, ω



Amplitude

$$\mathcal{A}(V\to \ell_1\bar{\ell}_2) = \bar{u}(p_1,s_1)\left[A_V^{\ell_1\ell_2}\gamma_\mu + B_V^{\ell_1\ell_2}\gamma_\mu\gamma_5 + \frac{C_V^{\ell_1\ell_2}}{m_V}(p_2-p_1)_\mu + \frac{iD_V^{\ell_1\ell_2}}{m_V}(p_2-p_1)_\mu\gamma_5\right] v(p_2,s_2)\ \epsilon^\mu(p)$$

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \overline{\ell}_2)}{\mathcal{B}(V \to e^+ e^-)} = \left(\frac{m_V \left(1 - y^2\right)}{4 \pi \alpha f_V Q_q} \right)^2 \left[\left(\left| A_V^{\ell_1 \ell_2} \right|^2 + \left| B_V^{\ell_1 \ell_2} \right|^2 \right) + \frac{1}{2} \left(1 - 2y^2\right) \left(\left| C_V^{\ell_1 \ell_2} \right|^2 + \left| D_V^{\ell_1 \ell_2} \right|^2 \right) + y \, \mathrm{Re} \left(A_V^{\ell_1 \ell_2} C_V^{\ell_1 \ell_2 *} + i B_V^{\ell_1 \ell_2} D_V^{\ell_1 \ell_2 *} \right) \right]$$

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+ e^-)} = \left(\frac{m_V\,(1-y^2)}{4\pi\alpha f_V Q_q}\right)^2 \left[\left(\left|A_V^{\ell_1\ell_2}\right|^2 + \left|B_V^{\ell_1\ell_2}\right|^2\right) + \frac{1}{2}\left(1-2y^2\right)\left(\left|C_V^{\ell_1\ell_2}\right|^2 + \left|D_V^{\ell_1\ell_2}\right|^2\right) + y\ \mathrm{Re}\left(A_V^{\ell_1\ell_2} C_V^{\ell_1\ell_2 *} + i B_V^{\ell_1\ell_2} D_V^{\ell_1\ell_2 *}\right)\right]$$

Dimensionless Constants

$$A_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[\sqrt{4\pi\alpha}\,Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + \kappa_V \left(C_{VL}^{q\ell_1\ell_2} + C_{VR}^{q\ell_1\ell_2}\right) + 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$B_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[-\sqrt{4\pi\alpha}\,Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - \kappa_V \left(C_{VL}^{q\ell_1\ell_2} - C_{VR}^{q\ell_1\ell_2}\right) - 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$C_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} y \left[\sqrt{4\pi\alpha}\,Q_q \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$D_V^{\ell_1\ell_2} = i\frac{f_V m_V}{\Lambda^2} y \left[-\sqrt{4\pi\alpha}\,Q_q \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+ e^-)} = \left(\frac{m_V \left(1-y^2\right)}{4\pi\alpha f_V Q_q} \right)^2 \left[\left(\left|A_V^{\ell_1\ell_2}\right|^2 + \left|B_V^{\ell_1\ell_2}\right|^2 \right) + \frac{1}{2}\left(1-2y^2\right) \left(\left|C_V^{\ell_1\ell_2}\right|^2 + \left|D_V^{\ell_1\ell_2}\right|^2 \right) + y \ \mathrm{Re}\left(A_V^{\ell_1\ell_2} C_V^{\ell_1\ell_2 *} + i B_V^{\ell_1\ell_2} D_V^{\ell_1\ell_2 *} \right) \right]$$

Dimensionless Constants

$$A_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} \left[\sqrt{4\pi\alpha} Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2} \right) + \kappa_V \left(C_{VL}^{q\ell_1\ell_2} + C_{VR}^{q\ell_1\ell_2} \right) + 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2} \right) \right]$$

$$B_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} \left[-\sqrt{4\pi\alpha} Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2} \right) - \kappa_V \left(C_{VL}^{q\ell_1\ell_2} - C_{VR}^{q\ell_1\ell_2} \right) - 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2} \right) \right]$$

$$C_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} y \left[\sqrt{4\pi\alpha} Q_q \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2} \right) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2} \right) \right]$$

$$D_V^{\ell_1\ell_2} = i \frac{f_V m_V}{\Lambda^2} y \left[-\sqrt{4\pi\alpha} Q_q \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2} \right) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2} \right) \right]$$

m_v = vector meson mass

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+ e^-)} = \left(\frac{m_V \left(1 - y^2\right)}{4\pi\alpha f_V Q_q} \right)^2 \left[\left(\left|A_V^{\ell_1 \ell_2}\right|^2 + \left|B_V^{\ell_1 \ell_2}\right|^2 \right) + \frac{1}{2} \left(1 - 2y^2\right) \left(\left|C_V^{\ell_1 \ell_2}\right|^2 + \left|D_V^{\ell_1 \ell_2}\right|^2 \right) + y \, \mathrm{Re} \left(A_V^{\ell_1 \ell_2} C_V^{\ell_1 \ell_2 *} + i B_V^{\ell_1 \ell_2} D_V^{\ell_1 \ell_2 *} \right) \right]$$

Dimensionless Constants

$$A_V^{\ell_1 \ell_2} = \frac{f_V m_V}{\Lambda^2} \left[\sqrt{4\pi\alpha} Q_q y^2 \left(C_{DL}^{\ell_1 \ell_2} + C_{DR}^{\ell_1 \ell_2} \right) + \kappa_V \left(C_{VL}^{q\ell_1 \ell_2} + C_{VR}^{q\ell_1 \ell_2} \right) + 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1 \ell_2} + C_{TR}^{q\ell_1 \ell_2} \right) \right]$$

$$B_V^{\ell_1 \ell_2} = \frac{f_V m_V}{\Lambda^2} \left[-\sqrt{4\pi\alpha} Q_q y^2 \left(C_{DL}^{\ell_1 \ell_2} - C_{DR}^{\ell_1 \ell_2} \right) - \kappa_V \left(C_{VL}^{q\ell_1 \ell_2} - C_{VR}^{q\ell_1 \ell_2} \right) - 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1 \ell_2} - C_{TR}^{q\ell_1 \ell_2} \right) \right]$$

$$C_V^{\ell_1 \ell_2} = \frac{f_V m_V}{\Lambda^2} y \left[\sqrt{4\pi\alpha} Q_q \left(C_{DL}^{\ell_1 \ell_2} + C_{DR}^{\ell_1 \ell_2} \right) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1 \ell_2} + C_{TR}^{q\ell_1 \ell_2} \right) \right]$$

$$D_V^{\ell_1 \ell_2} = i \frac{f_V m_V}{\Lambda^2} y \left[-\sqrt{4\pi\alpha} Q_q \left(C_{DL}^{\ell_1 \ell_2} - C_{DR}^{\ell_1 \ell_2} \right) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1 \ell_2} - C_{TR}^{q\ell_1 \ell_2} \right) \right]$$

m_v = vector meson mass

$y = m_2/m_V$

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V\to \ell_1\bar{\ell}_2)}{\mathcal{B}(V\to e^+e^-)} = \left(\frac{m_V\,(1-y^2)}{4\pi\alpha f_V Q_q}\right)^2 \left[\left(\left|A_V^{\ell_1\ell_2}\right|^2 + \left|B_V^{\ell_1\ell_2}\right|^2\right) + \frac{1}{2}\left(1-2y^2\right)\left(\left|C_V^{\ell_1\ell_2}\right|^2 + \left|D_V^{\ell_1\ell_2}\right|^2\right)\right.$$
$$\left. + y\ \mathrm{Re}\left(A_V^{\ell_1\ell_2} C_V^{\ell_1\ell_2 *} + i B_V^{\ell_1\ell_2} D_V^{\ell_1\ell_2 *}\right)\right]$$

Dimensionless Constants

$$A_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[\sqrt{4\pi\alpha}Q_q y^2\left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + \kappa_V\left(C_{VL}^{q\ell_1\ell_2} + C_{VR}^{q\ell_1\ell_2}\right) + 2y^2\kappa_V\frac{f_V^T}{f_V}G_F m_V m_q\left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$B_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[-\sqrt{4\pi\alpha}Q_q y^2\left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - \kappa_V\left(C_{VL}^{q\ell_1\ell_2} - C_{VR}^{q\ell_1\ell_2}\right) - 2y^2\kappa_V\frac{f_V^T}{f_V}G_F m_V m_q\left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$C_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}y\left[\sqrt{4\pi\alpha}Q_q\left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + 2\kappa_V\frac{f_V^T}{f_V}G_F m_V m_q\left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$D_V^{\ell_1\ell_2} = i\frac{f_V m_V}{\Lambda^2}y\left[-\sqrt{4\pi\alpha}Q_q\left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - 2\kappa_V\frac{f_V^T}{f_V}G_F m_V m_q\left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

m_v = vector meson mass

Q_q = quark charge (2/3,-1/3)

$y = m_2/m_V$

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+ e^-)} = \left(\frac{m_V (1-y^2)}{4\pi\alpha f_V Q_q}\right)^2 \left[\left(\left|A_V^{\ell_1\ell_2}\right|^2 + \left|B_V^{\ell_1\ell_2}\right|^2\right) + \frac{1}{2}(1-2y^2)\left(\left|C_V^{\ell_1\ell_2}\right|^2 + \left|D_V^{\ell_1\ell_2}\right|^2\right) + y \,\mathrm{Re}\left(A_V^{\ell_1\ell_2} C_V^{\ell_1\ell_2 *} + i B_V^{\ell_1\ell_2} D_V^{\ell_1\ell_2 *}\right)\right]$$

Dimensionless Constants

$$A_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[\boxed{\sqrt{4\pi\alpha}} Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + \kappa_V \left(C_{VL}^{q\ell_1\ell_2} + C_{VR}^{q\ell_1\ell_2}\right) + 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$B_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[-\boxed{\sqrt{4\pi\alpha}} Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - \kappa_V \left(C_{VL}^{q\ell_1\ell_2} - C_{VR}^{q\ell_1\ell_2}\right) - 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$C_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} y \left[\boxed{\sqrt{4\pi\alpha}} Q_q \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$D_V^{\ell_1\ell_2} = i\frac{f_V m_V}{\Lambda^2} y \left[-\boxed{\sqrt{4\pi\alpha}} Q_q \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

m_v = vector meson mass

Q_q = quark charge (2/3,-1/3)

$y = m_2/m_V$

α = fine structure constant

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+e^-)} = \left(\frac{m_V\,(1-y^2)}{4\pi\alpha f_V Q_q}\right)^2 \left[\left(\left|A_V^{\ell_1\ell_2}\right|^2 + \left|B_V^{\ell_1\ell_2}\right|^2\right) + \frac{1}{2}\left(1-2y^2\right)\left(\left|C_V^{\ell_1\ell_2}\right|^2 + \left|D_V^{\ell_1\ell_2}\right|^2\right) + y\,\mathrm{Re}\left(A_V^{\ell_1\ell_2} C_V^{\ell_1\ell_2 *} + i B_V^{\ell_1\ell_2} D_V^{\ell_1\ell_2 *}\right)\right]$$

Dimensionless Constants

$$A_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[\sqrt{4\pi\alpha}\,Q_q y^2\left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + \kappa_V\left(C_{VL}^{q\ell_1\ell_2} + C_{VR}^{q\ell_1\ell_2}\right) + 2y^2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$B_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[-\sqrt{4\pi\alpha}\,Q_q y^2\left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - \kappa_V\left(C_{VL}^{q\ell_1\ell_2} - C_{VR}^{q\ell_1\ell_2}\right) - 2y^2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$C_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} y\left[\sqrt{4\pi\alpha}\,Q_q \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$D_V^{\ell_1\ell_2} = i\frac{f_V m_V}{\Lambda^2} y\left[-\sqrt{4\pi\alpha}\,Q_q \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

m_v = vector meson mass

Q_q = quark charge (2/3,-1/3)

$y = m_2/m_V$

α = fine structure constant

κ_V = ½ (constant for pure q q bar states)

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+e^-)} = \left(\frac{m_V\,(1-y^2)}{4\pi\alpha f_V Q_q}\right)^2 \left[\left(\left|A_V^{\ell_1\ell_2}\right|^2 + \left|B_V^{\ell_1\ell_2}\right|^2\right) + \frac{1}{2}\left(1-2y^2\right)\left(\left|C_V^{\ell_1\ell_2}\right|^2 + \left|D_V^{\ell_1\ell_2}\right|^2\right) + y\ \mathrm{Re}\left(A_V^{\ell_1\ell_2} C_V^{\ell_1\ell_2 *} + i B_V^{\ell_1\ell_2} D_V^{\ell_1\ell_2 *}\right)\right]$$

Dimensionless Constants

$$A_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[\sqrt{4\pi\alpha}Q_q y^2\left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + \kappa_V\left(C_{VL}^{q\ell_1\ell_2} + C_{VR}^{q\ell_1\ell_2}\right) + 2y^2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$B_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[-\sqrt{4\pi\alpha}Q_q y^2\left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - \kappa_V\left(C_{VL}^{q\ell_1\ell_2} - C_{VR}^{q\ell_1\ell_2}\right) - 2y^2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$C_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} y\left[\sqrt{4\pi\alpha}Q_q \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$D_V^{\ell_1\ell_2} = i\frac{f_V m_V}{\Lambda^2} y\left[-\sqrt{4\pi\alpha}Q_q \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

Dipole operator dependence

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+ e^-)} = \left(\frac{m_V\,(1-y^2)}{4\pi\alpha f_V Q_q}\right)^2 \left[\left(\left|A_V^{\ell_1\ell_2}\right|^2 + \left|B_V^{\ell_1\ell_2}\right|^2\right) + \frac{1}{2}\left(1-2y^2\right)\left(\left|C_V^{\ell_1\ell_2}\right|^2 + \left|D_V^{\ell_1\ell_2}\right|^2\right) + y\ \mathrm{Re}\left(A_V^{\ell_1\ell_2} C_V^{\ell_1\ell_2 *} + i B_V^{\ell_1\ell_2} D_V^{\ell_1\ell_2 *}\right) \right]$$

Dimensionless Constants

$$A_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[\sqrt{4\pi\alpha}\,Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + \kappa_V \left(C_{VL}^{q\ell_1\ell_2} + C_{VR}^{q\ell_1\ell_2}\right) + 2y^2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$B_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[-\sqrt{4\pi\alpha}\,Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - \kappa_V \left(C_{VL}^{q\ell_1\ell_2} - C_{VR}^{q\ell_1\ell_2}\right) - 2y^2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$C_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} y \left[\sqrt{4\pi\alpha}\,Q_q \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$D_V^{\ell_1\ell_2} = i\frac{f_V m_V}{\Lambda^2} y \left[-\sqrt{4\pi\alpha}\,Q_q \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

Dipole operator dependence

Vector operator dependence

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+ e^-)} = \left(\frac{m_V \left(1-y^2\right)}{4\pi\alpha f_V Q_q} \right)^2 \left[\left(\left|A_V^{\ell_1\ell_2}\right|^2 + \left|B_V^{\ell_1\ell_2}\right|^2 \right) + \frac{1}{2}\left(1-2y^2\right) \left(\left|C_V^{\ell_1\ell_2}\right|^2 + \left|D_V^{\ell_1\ell_2}\right|^2 \right) + y \,\mathrm{Re}\left(A_V^{\ell_1\ell_2} C_V^{\ell_1\ell_2*} + i B_V^{\ell_1\ell_2} D_V^{\ell_1\ell_2*} \right) \right]$$

Dimensionless Constants

$$A_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} \left[\sqrt{4\pi\alpha} Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2} \right) + \kappa_V \left(C_{VL}^{q\ell_1\ell_2} + C_{VR}^{q\ell_1\ell_2} \right) + 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2} \right) \right]$$

$$B_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} \left[-\sqrt{4\pi\alpha} Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2} \right) - \kappa_V \left(C_{VL}^{q\ell_1\ell_2} - C_{VR}^{q\ell_1\ell_2} \right) - 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2} \right) \right]$$

$$C_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} y \left[\sqrt{4\pi\alpha} Q_q \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2} \right) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2} \right) \right]$$

$$D_V^{\ell_1\ell_2} = i \frac{f_V m_V}{\Lambda^2} y \left[-\sqrt{4\pi\alpha} Q_q \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2} \right) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2} \right) \right]$$

Dipole operator dependence

Vector operator dependence

Tensor operator dependence

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+ e^-)} = \left(\frac{m_V \left(1 - y^2\right)}{4\pi\alpha f_V Q_q} \right)^2 \left[\left(\left| A_V^{\ell_1 \ell_2} \right|^2 + \left| B_V^{\ell_1 \ell_2} \right|^2 \right) + \frac{1}{2} \left(1 - 2y^2\right) \left(\left| C_V^{\ell_1 \ell_2} \right|^2 + \left| D_V^{\ell_1 \ell_2} \right|^2 \right) + y \, \mathrm{Re} \left(A_V^{\ell_1 \ell_2} C_V^{\ell_1 \ell_2 *} + i B_V^{\ell_1 \ell_2} D_V^{\ell_1 \ell_2 *} \right) \right]$$

Dimensionless Constants

$$A_V^{\ell_1 \ell_2} = \frac{f_V m_V}{\Lambda^2} \left[\sqrt{4\pi\alpha} Q_q y^2 \left(C_{DL}^{\ell_1 \ell_2} + C_{DR}^{\ell_1 \ell_2} \right) + \kappa_V \left(C_{VL}^{q\ell_1 \ell_2} + C_{VR}^{q\ell_1 \ell_2} \right) + 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1 \ell_2} + C_{TR}^{q\ell_1 \ell_2} \right) \right]$$

$$B_V^{\ell_1 \ell_2} = \frac{f_V m_V}{\Lambda^2} \left[-\sqrt{4\pi\alpha} Q_q y^2 \left(C_{DL}^{\ell_1 \ell_2} - C_{DR}^{\ell_1 \ell_2} \right) - \kappa_V \left(C_{VL}^{q\ell_1 \ell_2} - C_{VR}^{q\ell_1 \ell_2} \right) - 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1 \ell_2} - C_{TR}^{q\ell_1 \ell_2} \right) \right]$$

$$C_V^{\ell_1 \ell_2} = \frac{f_V m_V}{\Lambda^2} y \left[\sqrt{4\pi\alpha} Q_q \left(C_{DL}^{\ell_1 \ell_2} + C_{DR}^{\ell_1 \ell_2} \right) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1 \ell_2} + C_{TR}^{q\ell_1 \ell_2} \right) \right]$$

$$D_V^{\ell_1 \ell_2} = i \frac{f_V m_V}{\Lambda^2} y \left[-\sqrt{4\pi\alpha} Q_q \left(C_{DL}^{\ell_1 \ell_2} - C_{DR}^{\ell_1 \ell_2} \right) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1 \ell_2} - C_{TR}^{q\ell_1 \ell_2} \right) \right]$$

f_V cancels out …

Two-body vector quarkonium decays

Branching ratio

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+ e^-)} = \left(\frac{m_V\,(1-y^2)}{4\pi\alpha f_V Q_q}\right)^2 \left[\left(\left|A_V^{\ell_1\ell_2}\right|^2 + \left|B_V^{\ell_1\ell_2}\right|^2\right) + \frac{1}{2}\left(1-2y^2\right)\left(\left|C_V^{\ell_1\ell_2}\right|^2 + \left|D_V^{\ell_1\ell_2}\right|^2\right) + y\ \mathrm{Re}\left(A_V^{\ell_1\ell_2} C_V^{\ell_1\ell_2 *} + i B_V^{\ell_1\ell_2} D_V^{\ell_1\ell_2 *}\right) \right]$$

Dimensionless Constants

$$A_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[\sqrt{4\pi\alpha}\,Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + \kappa_V \left(C_{VL}^{q\ell_1\ell_2} + C_{VR}^{q\ell_1\ell_2}\right) + 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$B_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}\left[-\sqrt{4\pi\alpha}\,Q_q y^2 \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - \kappa_V \left(C_{VL}^{q\ell_1\ell_2} - C_{VR}^{q\ell_1\ell_2}\right) - 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$C_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} y \left[\sqrt{4\pi\alpha}\,Q_q \left(C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}\right) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2}\right)\right]$$

$$D_V^{\ell_1\ell_2} = i\frac{f_V m_V}{\Lambda^2} y \left[-\sqrt{4\pi\alpha}\,Q_q \left(C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}\right) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q \left(C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2}\right)\right]$$

f_V cancels out …
except for the ratio of f_V^T/f_V

Two-body vector quarkonium decays

Decay constants used to constrain Wilson coefficients

State	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	J/ψ	$\psi(2S)$	ϕ	$\rho\,(\omega)$
f_V, MeV	649 ± 31	481 ± 39	539 ± 84	418 ± 9	294 ± 5	241 ± 18	209.4 ± 1.5

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*D. Becirevic, et al. Nucl. Phys. B. 883, 306 (2014).

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- Tensor decay constants are not well know
- Except $f_{J/\psi}^{T} = 410 \pm 10$ MeV *
- Assume $f_V^{T} = f_V$

*D. Becirevic, et al. Nucl. Phys. B. 883, 306 (2014).

Two-body vector quarkonium decays

Experimental upper limits of BR for 2-body vector decays and radiative lepton decays from the PDG.

$\ell_1\ell_2$	$\mu\tau$	$e\tau$	$e\mu$
$\mathcal{B}(\Upsilon(1S) \to \ell_1\ell_2)$	6.0×10^{-6}	–	–
$\mathcal{B}(\Upsilon(2S) \to \ell_1\ell_2)$	3.3×10^{-6}	3.2×10^{-6}	–
$\mathcal{B}(\Upsilon(3S) \to \ell_1\ell_2)$	3.1×10^{-6}	4.2×10^{-6}	–
$\mathcal{B}(J/\psi \to \ell_1\ell_2)$	2.0×10^{-6}	8.3×10^{-6}	1.6×10^{-7}
$\mathcal{B}(\phi \to \ell_1\ell_2)$	n/a	n/a	4.1×10^{-6}
$\mathcal{B}(\ell_2 \to \ell_1\gamma)$	4.4×10^{-8}	3.3×10^{-8}	5.7×10^{-13}

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$B(\mu \text{ to } e\gamma)_{\nu SM} \sim 10^{-54}$

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$\mathcal{B}(J/\psi \to \ell_1\ell_2)$	2.0×10^{-6}	8.3×10^{-6}	1.6×10^{-7}
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Dashes = no data

Two-body vector quarkonium decays

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$B(\mu \text{ to } e\gamma)_{\nu SM} \sim 10^{-54}$

Dashes = no data

n/a = forbidden by phase space

Two-body vector quarkonium decays

Constraints on Wilson coefficients of 4-fermion operators.

	Leptons	Initial state (quark)				
Wilson coefficient (GeV^{-2})	$\ell_1\ell_2$	$\Upsilon(1S)$ (b)	$\Upsilon(2S)$ (b)	$\Upsilon(3S)$ (b)	J/ψ (c)	ϕ (s)
$\left\lvert C_{VL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	n/a
	$e\tau$	–	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	n/a
	$e\mu$	–	–	–	1.0×10^{-5}	2×10^{-3}
$\left\lvert C_{VR}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	n/a
	$e\tau$	–	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	n/a
	$e\mu$	–	–	–	1.0×10^{-5}	2×10^{-3}
$\left\lvert C_{TL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	n/a
	$e\tau$	–	3.3×10^{-2}	3.2×10^{-2}	2.4	n/a
	$e\mu$	–	–	–	4.8	1×10^{4}
$\left\lvert C_{TR}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	n/a
	$e\tau$	–	3.3×10^{-2}	3.2×10^{-2}	2.4	n/a
	$e\mu$	–	–	–	4.8	1×10^{4}

Two-body vector quarkonium decays

Constraints on Wilson coefficients of 4-fermion operators.

	Leptons	Initial state (quark)				
Wilson coefficient (GeV^{-2})	$\ell_1\ell_2$	$\Upsilon(1S)$ (b)	$\Upsilon(2S)$ (b)	$\Upsilon(3S)$ (b)	J/ψ (c)	ϕ (s)
	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	n/a
$\left\lvert C_{VL}^{q\ell_1\ell_2}/\Lambda^2 \right\rvert$	$e\tau$	–	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	n/a
	$e\mu$	–	–	–	1.0×10^{-5}	2×10^{-3}
	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	n/a
$\left\lvert C_{VR}^{q\ell_1\ell_2}/\Lambda^2 \right\rvert$	$e\tau$	–	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	n/a
	$e\mu$	–	–	–	1.0×10^{-5}	2×10^{-3}
	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	n/a
$\left\lvert C_{TL}^{q\ell_1\ell_2}/\Lambda^2 \right\rvert$	$e\tau$	–	3.3×10^{-2}	3.2×10^{-2}	2.4	n/a
	$e\mu$	–	–	–	4.8	1×10^{4}
	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	n/a
$\left\lvert C_{TR}^{q\ell_1\ell_2}/\Lambda^2 \right\rvert$	$e\tau$	–	3.3×10^{-2}	3.2×10^{-2}	2.4	n/a
	$e\mu$	–	–	–	4.8	1×10^{4}

Two-body vector quarkonium decays

Constraints on Wilson coefficients of 4-fermion operators.

Wilson coefficient (GeV^{-2})	Leptons $\ell_1\ell_2$	Initial state (quark) $\Upsilon(1S)$ (b)	$\Upsilon(2S)$ (b)	$\Upsilon(3S)$ (b)	J/ψ (c)	ϕ (s)
$\left\lvert C_{VL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	n/a
	$e\tau$	–	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	n/a
	$e\mu$	–	–	–	1.0×10^{-5}	2×10^{-3}
	$e\mu$	–	–	–	1.0×10^{-5}	2×10^{-3}
$\left\lvert C_{TL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	n/a
	$e\tau$	–	3.3×10^{-2}	3.2×10^{-2}	2.4	n/a
	$e\mu$	–	–	–	4.8	1×10^{4}
$\left\lvert C_{TR}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	n/a
	$e\tau$	–	3.3×10^{-2}	3.2×10^{-2}	2.4	n/a
	$e\mu$	–	–	–	4.8	1×10^{4}

- Not a breakdown of the EFT!
- Existing data doesn't allow for strong constraints

Two-body vector quarkonium decays

Constraints on Wilson coefficients of dipole operators.

Dipole Wilson coefficient (GeV^{-2})	Leptons $\ell_1\ell_2$	Initial state $\Upsilon(1S)$ (b)	$\Upsilon(2S)$ (b)	$\Upsilon(3S)$ (b)	J/ψ (c)	$\phi(s)$	$\ell_2 \to \ell_1\gamma$
	$\mu\tau$	2.0×10^{-4}	1.6×10^{-4}	1.4×10^{-4}	2.5×10^{-4}	n/a	2.6×10^{-10}
$\left\|C_{DL}^{\ell_1\ell_2}/\Lambda^2\right\|$	$e\tau$	–	1.6×10^{-4}	1.6×10^{-4}	5.3×10^{-4}	n/a	2.7×10^{-10}
	$e\mu$	–	–	–	1.1×10^{-3}	0.2	3.1×10^{-7}
	$\mu\tau$	2.0×10^{-4}	1.6×10^{-4}	1.4×10^{-4}	2.5×10^{-4}	n/a	2.6×10^{-10}
$\left\|C_{DR}^{q\ell_1\ell_2}/\Lambda^2\right\|$	$e\tau$	–	1.6×10^{-4}	1.6×10^{-4}	5.3×10^{-4}	n/a	2.7×10^{-10}
	$e\mu$	–	–	–	1.1×10^{-3}	0.2	3.1×10^{-7}

Two-body vector quarkonium decays

Constraints on Wilson coefficients of dipole operators.

Dipole Wilson coefficient (GeV^{-2})	Leptons $\ell_1\ell_2$	Initial state $\Upsilon(1S)$ (b)	$\Upsilon(2S)$ (b)	$\Upsilon(3S)$ (b)	J/ψ (c)	$\phi(s)$	$\ell_2 \to \ell_1\gamma$
$\left\|C_{DL}^{\ell_1\ell_2}/\Lambda^2\right\|$	$\mu\tau$	2.0×10^{-4}	1.6×10^{-4}	1.4×10^{-4}	2.5×10^{-4}	n/a	2.6×10^{-10}
	$e\tau$	–	1.6×10^{-4}	1.6×10^{-4}	5.3×10^{-4}	n/a	2.7×10^{-10}
	$e\mu$	–	–	–	1.1×10^{-3}	0.2	3.1×10^{-7}
$\left\|C_{DR}^{q\ell_1\ell_2}/\Lambda^2\right\|$	$\mu\tau$	2.0×10^{-4}	1.6×10^{-4}	1.4×10^{-4}	2.5×10^{-4}	n/a	2.6×10^{-10}
	$e\tau$	–	1.6×10^{-4}	1.6×10^{-4}	5.3×10^{-4}	n/a	2.7×10^{-10}
	$e\mu$	–	–	–	1.1×10^{-3}	0.2	3.1×10^{-7}

- Radiative lepton decays give much stronger constraints
- Vector decay constraints are complimentary

2-body pseudoscalar meson decays

$$\langle 0|\overline{q}\gamma^\mu\gamma_5 q|P(p)\rangle \;=\; -if_P p^\mu$$

Decay constant

$$\langle 0|\frac{\alpha_s}{4\pi}G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}|P(p)\rangle \;=\; a_P$$

Anomalous matrix element

2-body pseudoscalar meson decays

$$\langle 0|\overline{q}\gamma^\mu\gamma_5 q|P(p)\rangle = -if_P p^\mu$$

Decay constant

$$\langle 0|\frac{\alpha_s}{4\pi}G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}|P(p)\rangle = a_P$$

Anomalous matrix element

P = any meson with quantum numbers 0^{-+} i.e. $\eta_{b(c)}$, $\eta^{(\prime)}$, π^0, B, D, K

2-body pseudoscalar meson decays

$$\langle 0|\overline{q}\gamma^{\mu}\gamma_5 q|P(p)\rangle = -if_P p^{\mu}$$

Decay constant

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Anomalous matrix element

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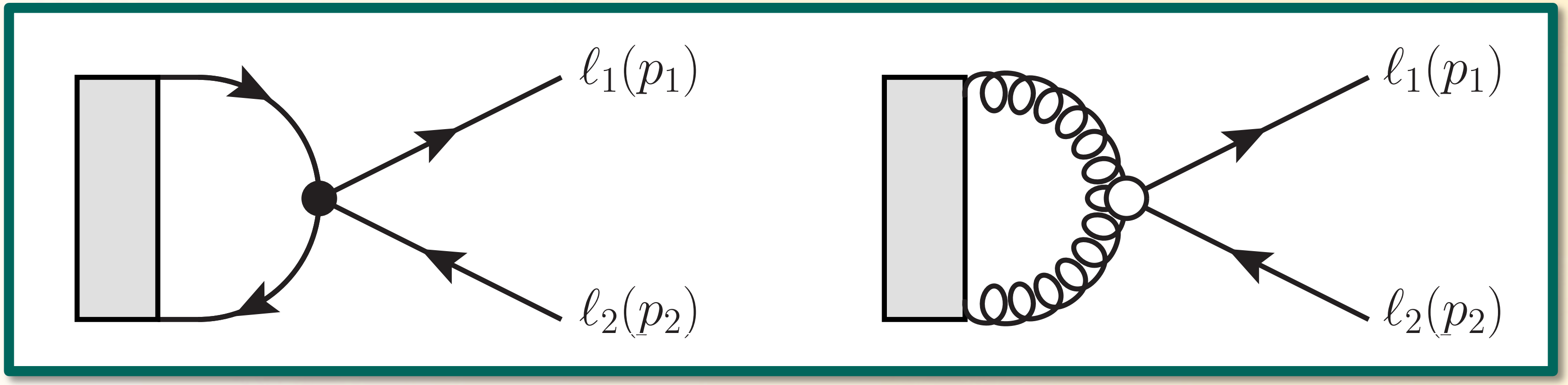

Amplitude

$$\mathcal{A}(P \to \ell_1\overline{\ell}_2) = \overline{u}(p_1, s_1)\left[E_P^{\ell_1\ell_2} + iF_P^{\ell_1\ell_2}\gamma_5\right]v(p_2, s_2)$$

2-body pseudoscalar meson decays

Branching ratio

$$\mathcal{B}(P \to \ell_1 \overline{\ell}_2) = \frac{m_P}{8\pi\Gamma_P}\left(1-y^2\right)^2\left[\left|E_P^{\ell_1\ell_2}\right|^2 + \left|F_P^{\ell_1\ell_2}\right|^2\right]$$

2-body pseudoscalar meson decays

Branching ratio

$$\mathcal{B}(P \to \ell_1 \bar{\ell}_2) = \frac{m_P}{8\pi\Gamma_P}\left(1-y^2\right)^2 \left[\left|E_P^{\ell_1\ell_2}\right|^2 + \left|F_P^{\ell_1\ell_2}\right|^2\right]$$

Dimensionless Constants

$$E_P^{\ell_1\ell_2} = y\frac{m_P}{4\Lambda^2}\left[-if_P\left[2\left(C_{AL}^{q\ell_1\ell_2} + C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2} + C_{PR}^{q\ell_1\ell_2}\right)\right] + 9G_F a_P\left(C_{\widetilde{G}L}^{\ell_1\ell_2} + C_{\widetilde{G}R}^{\ell_1\ell_2}\right)\right]$$
$$F_P^{\ell_1\ell_2} = -y\frac{m_P}{4\Lambda^2}\left[f_P\left[2\left(C_{AL}^{q\ell_1\ell_2} - C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2} - C_{PR}^{q\ell_1\ell_2}\right)\right] + 9iG_F a_P\left(C_{\widetilde{G}L}^{\ell_1\ell_2} - C_{\widetilde{G}R}^{\ell_1\ell_2}\right)\right]$$

2-body pseudoscalar meson decays

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Dimensionless Constants

$$E_P^{\ell_1\ell_2} = y\frac{m_P}{4\Lambda^2}\left[-if_P\left[2\left(C_{AL}^{q\ell_1\ell_2} + C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2} + C_{PR}^{q\ell_1\ell_2}\right)\right] + 9G_F a_P\left(C_{\tilde{G}L}^{\ell_1\ell_2} + C_{\tilde{G}R}^{\ell_1\ell_2}\right)\right]$$

$$F_P^{\ell_1\ell_2} = -y\frac{m_P}{4\Lambda^2}\left[f_P\left[2\left(C_{AL}^{q\ell_1\ell_2} - C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2} - C_{PR}^{q\ell_1\ell_2}\right)\right] + 9iG_F a_P\left(C_{\tilde{G}L}^{\ell_1\ell_2} - C_{\tilde{G}R}^{\ell_1\ell_2}\right)\right]$$

m_P = pseudoscalar meson mass

2-body pseudoscalar meson decays

Branching ratio

$$\mathcal{B}(P \to \ell_1 \bar{\ell}_2) = \frac{m_P}{8\pi\Gamma_P}\left(1 - y^2\right)^2 \left[\left|E_P^{\ell_1\ell_2}\right|^2 + \left|F_P^{\ell_1\ell_2}\right|^2\right]$$

Dimensionless Constants

$$E_P^{\ell_1\ell_2} = y\frac{m_P}{4\Lambda^2}\left[-if_P\left[2\left(C_{AL}^{q\ell_1\ell_2} + C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2} + C_{PR}^{q\ell_1\ell_2}\right)\right] + 9G_F a_P\left(C_{\widetilde{G}L}^{\ell_1\ell_2} + C_{\widetilde{G}R}^{\ell_1\ell_2}\right)\right]$$

$$F_P^{\ell_1\ell_2} = -y\frac{m_P}{4\Lambda^2}\left[f_P\left[2\left(C_{AL}^{q\ell_1\ell_2} - C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2} - C_{PR}^{q\ell_1\ell_2}\right)\right] + 9iG_F a_P\left(C_{\widetilde{G}L}^{\ell_1\ell_2} - C_{\widetilde{G}R}^{\ell_1\ell_2}\right)\right]$$

m_P = pseudoscalar meson mass

$y = m_2/m_P$

2-body pseudoscalar meson decays

Branching ratio

$$\mathcal{B}(P \to \ell_1 \bar{\ell}_2) = \frac{m_P}{8\pi\Gamma_P}\left(1-y^2\right)^2 \left[\left|E_P^{\ell_1\ell_2}\right|^2 + \left|F_P^{\ell_1\ell_2}\right|^2\right]$$

Dimensionless Constants

$$E_P^{\ell_1\ell_2} = y\frac{m_P}{4\Lambda^2}\left[-if_P\left[2\left(C_{AL}^{q\ell_1\ell_2}+C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2}+C_{PR}^{q\ell_1\ell_2}\right)\right] + 9G_F a_P\left(C_{\tilde{G}L}^{\ell_1\ell_2}+C_{\tilde{G}R}^{\ell_1\ell_2}\right)\right]$$

$$F_P^{\ell_1\ell_2} = -y\frac{m_P}{4\Lambda^2}\left[f_P\left[2\left(C_{AL}^{q\ell_1\ell_2}-C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2}-C_{PR}^{q\ell_1\ell_2}\right)\right] + 9iG_F a_P\left(C_{\tilde{G}L}^{\ell_1\ell_2}-C_{\tilde{G}R}^{\ell_1\ell_2}\right)\right]$$

m_P = pseudoscalar meson mass

$y = m_2/m_P$

Γ_P = total decay rate

2-body pseudoscalar meson decays

Branching ratio

$$\mathcal{B}(P \to \ell_1 \bar{\ell}_2) = \frac{m_P}{8\pi\Gamma_P}\left(1-y^2\right)^2\left[\left|E_P^{\ell_1\ell_2}\right|^2 + \left|F_P^{\ell_1\ell_2}\right|^2\right]$$

Dimensionless Constants

$$E_P^{\ell_1\ell_2} = y\frac{m_P}{4\Lambda^2}\left[-if_P\left[2\left(C_{AL}^{q\ell_1\ell_2} + C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2} + C_{PR}^{q\ell_1\ell_2}\right)\right] + 9G_F a_P\left(C_{\tilde{G}L}^{\ell_1\ell_2} + C_{\tilde{G}R}^{\ell_1\ell_2}\right)\right]$$

$$F_P^{\ell_1\ell_2} = -y\frac{m_P}{4\Lambda^2}\left[f_P\left[2\left(C_{AL}^{q\ell_1\ell_2} - C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2} - C_{PR}^{q\ell_1\ell_2}\right)\right] + 9iG_F a_P\left(C_{\tilde{G}L}^{\ell_1\ell_2} - C_{\tilde{G}R}^{\ell_1\ell_2}\right)\right]$$

m_P = pseudoscalar meson mass

$y = m_2/m_P$

Γ_P = total decay rate

Axial operator dependence

2-body pseudoscalar quarkonium decays

Branching ratio

$$\mathcal{B}(P \to \ell_1 \bar{\ell}_2) = \frac{m_P}{8\pi\Gamma_P}\left(1-y^2\right)^2\left[\left|E_P^{\ell_1\ell_2}\right|^2 + \left|F_P^{\ell_1\ell_2}\right|^2\right]$$

Dimensionless Constants

$$E_P^{\ell_1\ell_2} = y\frac{m_P}{4\Lambda^2}\left[-if_P\left[2\left(C_{AL}^{q\ell_1\ell_2}+C_{AR}^{q\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{q\ell_1\ell_2}+C_{PR}^{q\ell_1\ell_2}\right)\right] + 9G_F a_P\left(C_{\widetilde{G}L}^{\ell_1\ell_2}+C_{\widetilde{G}R}^{\ell_1\ell_2}\right)\right]$$

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Pseudoscalar operator dependence

Gluonic operator dependence

2-body pseudoscalar meson decays

Decay constants used to constrain Wilson coefficients

State	η_b	η_c	$\eta, u(d)$	η, s	$\eta', u(d)$	η', s	π
f_P^q, MeV	667 ± 6	387 ± 7	108 ± 3	-111 ± 6	89 ± 3	136 ± 6	130.41 ± 0.20

State	B_d^0	B_s^0	D^0	K_L^0
f_P, MeV	186 ± 4	224 ± 4	207.4 ± 3.8	155.0 ± 1.9

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- $a_\eta = -0.022 \pm 0.002$ GeV^3
- $a_{\eta'} = -0.057 \pm 0.002$ GeV^3

2-body pseudoscalar meson decays

Experimental upper limits of BR for 2-body pseudoscalar decays from the PDG.

$\ell_1\ell_2$	$\mu\tau$	$e\tau$	$e\mu$
$\mathcal{B}(\eta \to \ell_1\ell_2)$	n/a	n/a	6×10^{-6}
$\mathcal{B}(\eta' \to \ell_1\ell_2)$	n/a	n/a	4.7×10^{-4}
$\mathcal{B}(\pi_0 \to \ell_1\ell_2)$	n/a	n/a	3.6×10^{-10}
$\mathcal{B}(B_d^0 \to \ell_1\ell_2)$	2.2×10^{-5}	2.8×10^{-5}	2.8×10^{-9}
$\mathcal{B}(B_s^0 \to \ell_1\ell_2)$	–	–	1.1×10^{-8}
$\mathcal{B}(D^0 \to \ell_1\ell_2)$	n/a	–	2.6×10^{-7}
$\mathcal{B}(K_L^0 \to \ell_1\ell_2)$	n/a	n/a	4.7×10^{-12}

2-body pseudoscalar quarkonium decays

Constraints on Wilson coefficients of 4-fermion operators.

	Leptons			Initial state			
Wilson coefficient	$\ell_1\ell_2$	η_b	η_c	$\eta(u/d)$	$\eta(s)$	$\eta'(u/d)$	$\eta'(s)$
	$\mu\tau$	–	–	n/a	n/a	n/a	n/a
$\left\lvert C_{AL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$e\tau$	–	–	n/a	n/a	n/a	n/a
	$e\mu$	–	–	3×10^{-3}	2×10^{-3}	2.1×10^{-1}	1.9×10^{-1}
	$\mu\tau$	–	–	n/a	n/a	n/a	n/a
$\left\lvert C_{AR}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$e\tau$	–	–	n/a	n/a	n/a	n/a
	$e\mu$	–	–	3×10^{-3}	2×10^{-3}	2.1×10^{-1}	1.9×10^{-1}
	$\mu\tau$	–	–	n/a	n/a	n/a	n/a
$\left\lvert C_{PL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$e\tau$	–	–	n/a	n/a	n/a	n/a
	$e\mu$	–	–	2×10^{3}	1×10^{3}	3.9×10^{4}	3.6×10^{4}
	$\mu\tau$	–	–	n/a	n/a	n/a	n/a
$\left\lvert C_{PR}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$e\tau$	–	–	n/a	n/a	n/a	n/a
	$e\mu$	–	–	2×10^{3}	1×10^{3}	3.9×10^{4}	3.6×10^{4}

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$\left\lvert C_{AL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	–	–	n/a	n/a	n/a	n/a
	$e\tau$	–	–	n/a	n/a	n/a	n/a
	$e\mu$	–	–	3×10^{-3}	2×10^{-3}	2.1×10^{-1}	1.9×10^{-1}
$\left\lvert C_{AR}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	–	–	n/a	n/a	n/a	n/a
	$e\tau$	–	–	n/a	n/a	n/a	n/a
	$e\mu$	–	–	3×10^{-3}	2×10^{-3}	2.1×10^{-1}	1.9×10^{-1}
$\left\lvert C_{PL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	–	–	n/a	n/a	n/a	n/a
	$e\tau$	–	–	n/a	n/a	n/a	n/a
	$e\mu$	–	–	2×10^{3}	1×10^{3}	3.9×10^{4}	3.6×10^{4}
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	$\mu\tau$	–	–	n/a	n/a	n/a	n/a
$\left\lvert C_{AL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$e\tau$	–	–	n/a	n/a	n/a	n/a
	$e\mu$	–	–	3×10^{-3}	2×10^{-3}	2.1×10^{-1}	1.9×10^{-1}

- Not a breakdown of the EFT!
- Existing data doesn't allow for strong constraints

	$e\mu$	–	–	3×10^{-3}	2×10^{-3}	2.1×10^{-1}	1.9×10^{-1}
	$\mu\tau$	–	–	n/a	n/a	n/a	n/a
$\left\lvert C_{PL}^{q\ell_1\ell_2}/\Lambda^2\right\rvert$	$e\tau$	–	–	n/a	n/a	n/a	n/a
	$e\mu$	–	–	2×10^{3}	1×10^{3}	3.9×10^{4}	3.6×10^{4}
	$\mu\tau$	–	–	n/a	n/a	n/a	n/a
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	$e\mu$	–	–	2×10^{3}	1×10^{3}	3.9×10^{4}	3.6×10^{4}

2-body pseudoscalar quarkonium decays

Constraints on Wilson coefficients of gluonic operators.

Gluonic Wilson coefficient (GeV^{-2})	Leptons $\ell_1\ell_2$	Initial state η_b	η_c	η	η'
$\left\|C_{GL}^{\ell_1\ell_2}/\Lambda^2\right\|$	$e\mu$	–	–	2×10^2	5.0×10^3
$\left\|C_{GR}^{\ell_1\ell_2}/\Lambda^2\right\|$	$e\mu$	–	–	2×10^2	5.0×10^3

2-body pseudoscalar quarkonium decays

Constraints on Wilson coefficients of gluonic operators.

Gluonic Wilson	Leptons			Initial state	
coefficient (GeV^{-2})	$\ell_1\ell_2$	η_b	η_c	η	η'
$\left\lvert C_{GL}^{\ell_1\ell_2}/\Lambda^2 \right\rvert$	$e\mu$	–	–	2×10^2	5.0×10^3
$\left\lvert C_{GR}^{\ell_1\ell_2}/\Lambda^2 \right\rvert$	$e\mu$	–	–	2×10^2	5.0×10^3

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Constraints on Wilson coefficients of gluonic operators.

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$\left\lvert C_{GL}^{\ell_1\ell_2}/\Lambda^2 \right\rvert$	$e\mu$	$-$	$-$	2×10^2	5.0×10^3
$\left\lvert C_{GR}^{\ell_1\ell_2}/\Lambda^2 \right\rvert$	$e\mu$	$-$	$-$	2×10^2	5.0×10^3

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2-body pseudoscalar meson decays

Constraints on Wilson coefficients of 4-fermion operators.

	Leptons		Initial state		
Wilson coefficient	$\ell_1\ell_2$	$B_d^0\,(d\bar{b})$	$B_s^0\,(s\bar{b})$	$D^0\,(c\bar{u})$	$K_L^0\,\left(\frac{d\bar{s}-s\bar{d}}{\sqrt{2}}\right)$
$\left\lvert C_{AL}^{q_1q_2\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	2.3×10^{-8}	–	n/a	n/a
	$e\tau$	2.6×10^{-8}	–	–	n/a
	$e\mu$	3.9×10^{-9}	6.3×10^{-9}	1.1×10^{-7}	5.0×10^{-12}
$\left\lvert C_{AR}^{q_1q_2\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	2.3×10^{-8}	–	n/a	n/a
	$e\tau$	2.6×10^{-8}	–	–	n/a
	$e\mu$	3.9×10^{-9}	6.3×10^{-9}	1.1×10^{-7}	5.0×10^{-12}
$\left\lvert C_{PL}^{q_1q_2\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	7.1×10^{-5}	–	n/a	n/a
	$e\tau$	8.0×10^{-5}	–	–	n/a
	$e\mu$	1.2×10^{-5}	1.9×10^{-5}	2.7×10^{-3}	1.7×10^{-6}
$\left\lvert C_{PR}^{q_1q_2\ell_1\ell_2}/\Lambda^2\right\rvert$	$\mu\tau$	7.1×10^{-5}	–	n/a	n/a
	$e\tau$	8.0×10^{-5}	–	–	n/a
	$e\mu$	1.2×10^{-5}	1.9×10^{-5}	2.7×10^{-3}	1.7×10^{-6}

2-body scalar quarkonium decays

$\langle 0|\bar{q}q|S(p)\rangle = -im_S f_S$ Decay constant

$\langle 0|\frac{\alpha_s}{4\pi}G^{a\mu\nu}G^a_{\mu\nu}|S(p)\rangle = a_S$ Anomalous matrix element

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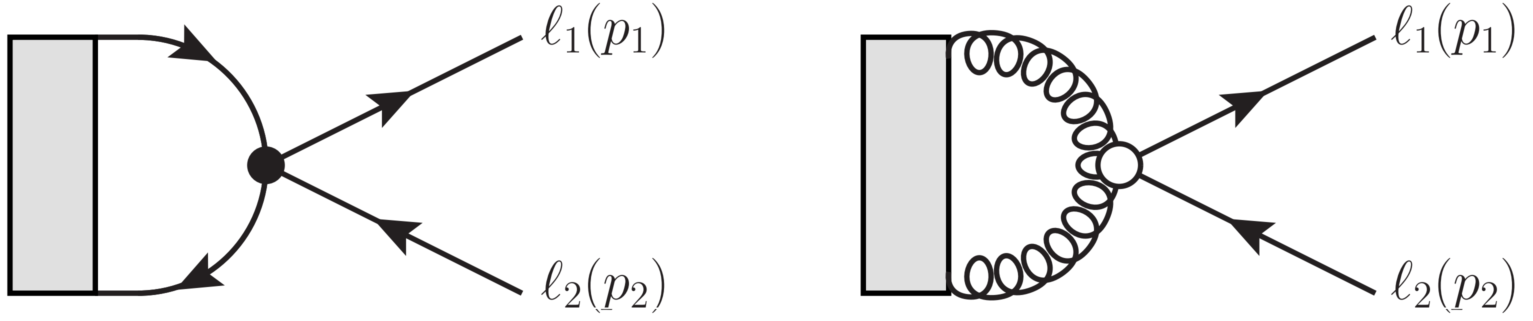

Amplitude

$$\mathcal{A}(S \to \ell_1\overline{\ell}_2) = \overline{u}(p_1, s_1)\left[E_S^{\ell_1\ell_2} + iF_S^{\ell_1\ell_2}\gamma_5\right]v(p_2, s_2)$$

2-body scalar quarkonium decays

Branching ratio

$$\mathcal{B}(S \to \ell_1 \overline{\ell}_2) = \frac{m_S}{8\pi\Gamma_S}\left(1 - y^2\right)^2 \left[\left|E_S^{\ell_1\ell_2}\right|^2 + \left|F_S^{\ell_1\ell_2}\right|^2\right]$$

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$$E_S^{\ell_1\ell_2} = y\frac{m_S G_F}{4\Lambda^2}\left[2if_S m_S m_q \left(C_{SL}^{ql_1l_2} + C_{SR}^{ql_1l_2}\right) + 9a_S\left(C_{GL}^{ql_1l_2} + C_{GR}^{ql_1l_2}\right)\right]$$

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  - Radiative decays of $\Upsilon(2S)$, $\Upsilon(3S)$, $\psi(2S)$, $\psi(3770)$

3-body vector quarkonium decays
Resonant transitions

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3-body vector quarkonium decays Resonant transitions

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- If soft γ can be tagged at B factories then:

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- Quite useful:

$$\mathcal{B}(\psi(2S) \to \gamma \chi_{c0}(1P)) = 9.99 \pm 0.27\% \ ,$$

$$\mathcal{B}(\psi(3770) \to \gamma \chi_{c0}(1P)) = 0.73 \pm 0.09\%$$

3-body vector quarkonium decays Resonant transitions

- V to γ (S to $l_1 l_2$) may be used to study scalar 2-body decays
- If soft γ can be tagged at B factories then:

$$\mathcal{B}(V \to \gamma \ell_1 \bar{\ell}_2) = \mathcal{B}(V \to \gamma M) \mathcal{B}(M \to \ell_1 \bar{\ell}_2)$$

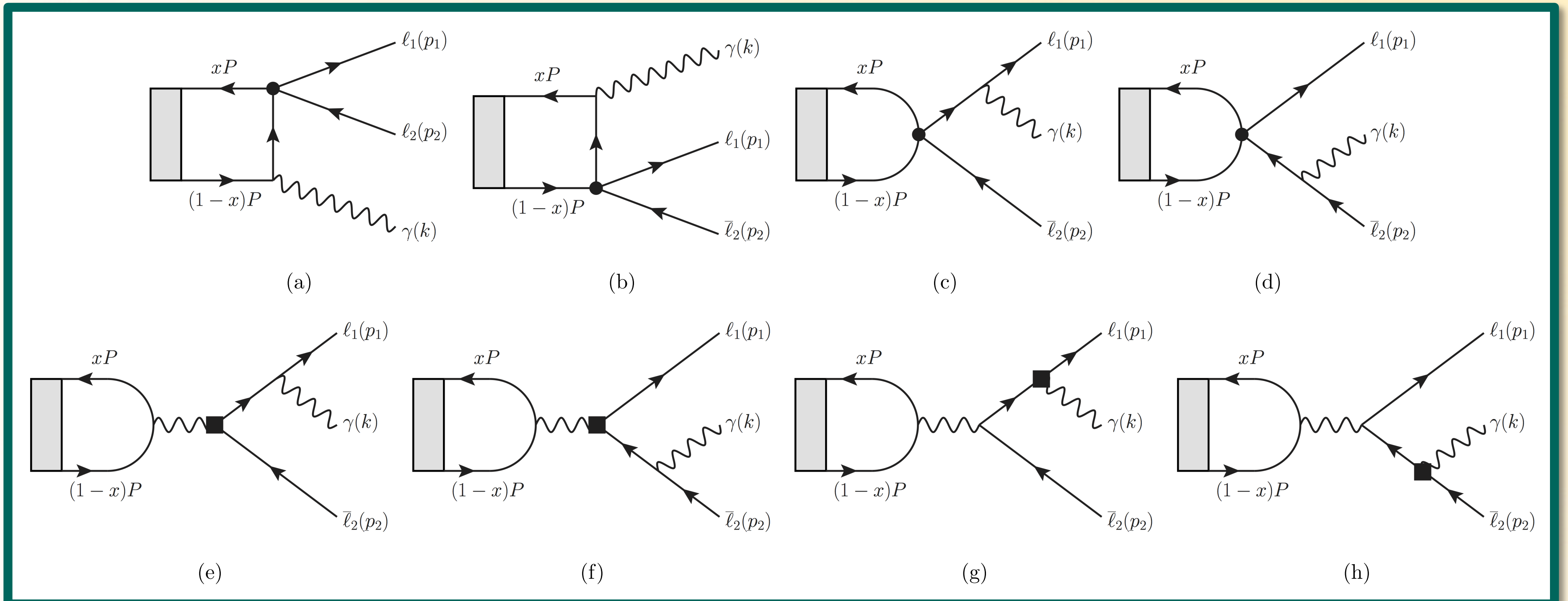
- Quite useful:

$$\mathcal{B}(\Upsilon(2S) \to \gamma \chi_{b0}(1P)) = 3.8 \pm 0.4\% \ ,$$

$$\mathcal{B}(\Upsilon(3S) \to \gamma \chi_{b0}(1P)) = 0.27 \pm 0.04\% \ ,$$

$$\mathcal{B}(\Upsilon(3S) \to \gamma \chi_{b0}(2P)) = 5.9 \pm 0.6\% \ .$$

3-body vector quarkonium decays
Nonresonant transitions



Diagrams for V to $\gamma\, l_1 l_2$

3-body vector quarkonium decays Nonresonant transitions

$$\Psi_V = \frac{I_c}{\sqrt{6}}\Phi_V(x)\left(m_V\gamma^\alpha + ip^\beta\sigma^{\alpha\beta}\right)\epsilon^\alpha(p)$$

wave function

$$\Phi_V(x) = \frac{f_V}{2\sqrt{6}}\delta(x-1/2)$$

distribution amplitude

$$\langle 0|\bar{q}\Gamma^\mu q|V\rangle = \int_0^1 \mathrm{Tr}[\Gamma^\mu\Psi_V]dx$$

nonlocal matrix element

3-body vector quarkonium decays Nonresonant transitions

Differential decay rates

$$\frac{d\Gamma^A_{V\to\gamma\ell_1\bar{\ell}_2}}{dm_{12}^2} = \frac{1}{9}\frac{\alpha Q_q^2}{(4\pi)^2}\frac{f_V^2}{\Lambda^4}\left(C_{AL}^2 + C_{AR}^2\right)\frac{\left(m_V^2 - m_{12}^2\right)\left(2m_V^2 y^2 + m_{12}^2\right)\left(m_V^2 y^2 - m_{12}^2\right)^2}{m_V m_{12}^6}$$

$$\frac{d\Gamma^S_{V\to\gamma\ell_1\bar{\ell}_2}}{dm_{12}^2} = \frac{1}{24}\frac{\alpha Q_q^2}{(4\pi)^2}\frac{f_V^2 G_F^2 m_V}{\Lambda^4}\left(C_{SL}^2 + C_{SR}^2\right)\frac{y^2\left(m_V^2 - m_{12}^2\right)\left(m_V^2 y^2 - m_{12}^2\right)^2}{m_{12}^2}$$

$$\frac{d\Gamma^P_{V\to\gamma\ell_1\bar{\ell}_2}}{dm_{12}^2} = \frac{1}{24}\frac{\alpha Q_q^2}{(4\pi)^2}\frac{f_V^2 G_F^2 m_V}{\Lambda^4}\left(C_{PL}^2 + C_{PR}^2\right)\frac{y^2\left(m_V^2 - m_{12}^2\right)\left(m_V^2 y^2 - m_{12}^2\right)^2}{m_{12}^2}$$

$m_{12}^2 = (P-k)^2$

3-body vector quarkonium decays Nonresonant transitions

Total decay rates

$$\Gamma_A(V \to \gamma \ell_1 \bar{\ell}_2) = \frac{1}{18} \frac{\alpha Q_q^2}{(4\pi)^2} \frac{f_V^2 m_V^3}{\Lambda^4} \left(C_{AL}^2 + C_{AR}^2\right) f(y^2)$$ Axial

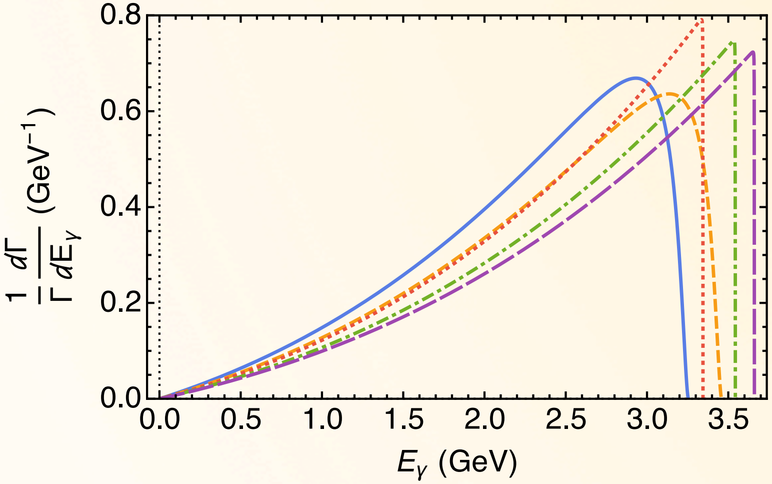
$$\Gamma_S(V \to \gamma \ell_1 \bar{\ell}_2) = \frac{1}{144} \frac{\alpha Q_q^2}{(4\pi)^2} \frac{f_V^2 G_F^2 m_V^7}{\Lambda^4} \left(C_{SL}^2 + C_{SR}^2\right) y^2 f(y^2)$$ Scalar

$$\Gamma_P(V \to \gamma \ell_1 \bar{\ell}_2) = \frac{1}{144} \frac{\alpha Q_q^2}{(4\pi)^2} \frac{f_V^2 G_F^2 m_V^7}{\Lambda^4} \left(C_{PL}^2 + C_{PR}^2\right) y^2 f(y^2)$$ Pseudoscalar

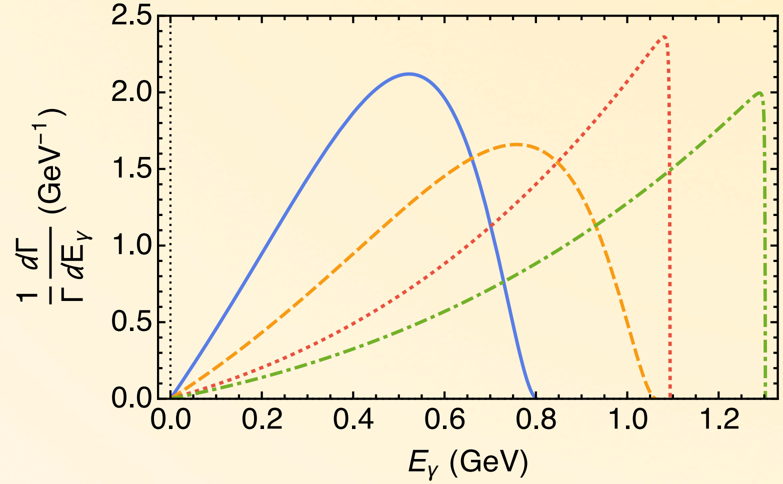
$$f(y^2) = 1 - 6y^2 - 12y^4 \log(y) + 3y^4 + 2y^6$$

3-body vector quarkonium decays
Nonresonant transitions

Axial operator differential decay rates



(a)

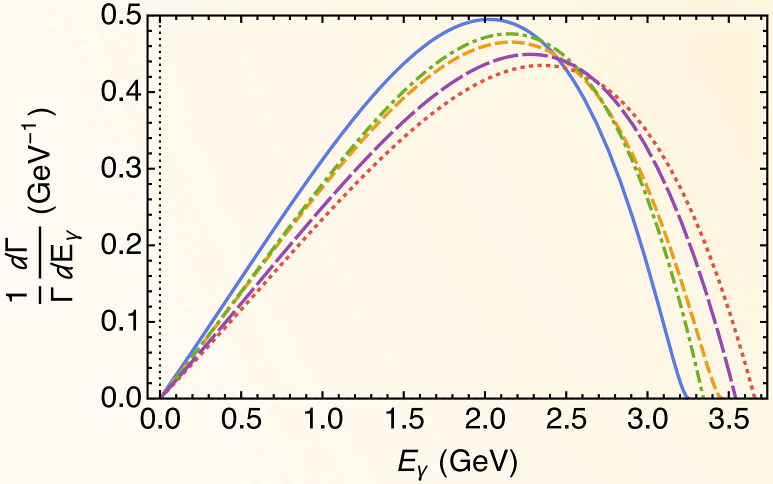


(b)

(a) $\Upsilon(1S) \to \gamma\,\mu\,\tau$ or $\gamma\,e\,\tau$ (solid blue), $\Upsilon(2S) \to \gamma\,\mu\,\tau$ or $\gamma\,e\,\tau$ (short-dashed gold), $\Upsilon(3S) \to \gamma\,\mu\,\tau$ or $\gamma\,e\,\tau$ (dotted red), $\Upsilon(1S) \to \gamma\,e\,\mu$ (dot-dashed green), $\Upsilon(2S) \to \gamma\,e\,\mu$ and $\Upsilon(3S) \to \gamma\,e\,\mu$ (long-dashed purple); (b) $J/\psi \to \gamma\,\mu\,\tau$ or $\gamma\,e\,\tau$ (solid blue), $\psi(2S) \to \gamma\,\mu\,\tau$ or $\gamma\,e\,\tau$ (short-dashed gold), $J\psi \to \gamma\,e\,\mu$ (dotted red), $\psi(2S) \to \gamma\,e\,\mu$ (dot-dashed green)

3-body vector quarkonium decays
Nonresonant transitions

Scalar/Pseudoscalar operator differential decay rates



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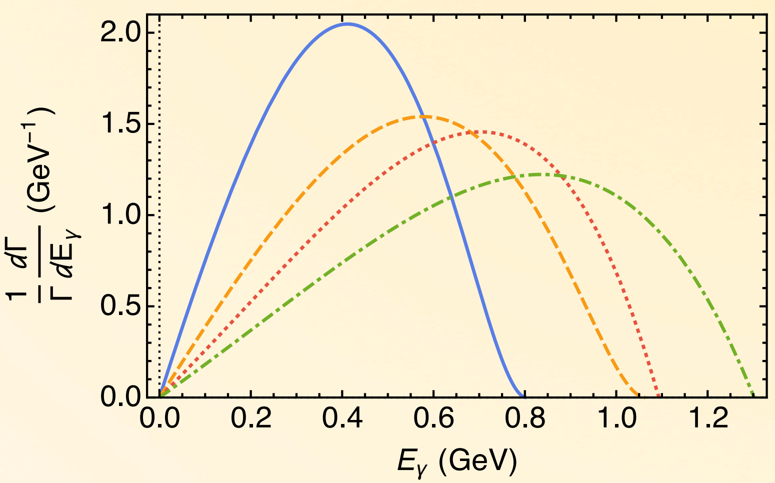

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(a) $\Upsilon(1S) \to \gamma\,\mu\,\tau$ or $\gamma\,e\,\tau$ (solid blue), $\Upsilon(2S) \to \gamma\,\mu\,\tau$ or $\gamma\,e\,\tau$ (short-dashed gold), $\Upsilon(3S) \to \gamma\,\mu\,\tau$ or $\gamma\,e\,\tau$ (dotted red), $\Upsilon(1S) \to \gamma\,e\,\mu$ (dot-dashed green), $\Upsilon(2S) \to \gamma\,e\,\mu$ and $\Upsilon(3S) \to \gamma\,e\,\mu$ (long-dashed purple); (b) $J/\psi \to \gamma\,\mu\,\tau$ or $\gamma\,e\,\tau$ (solid blue), $\psi(2S) \to \gamma\,\mu\,\tau$ or $\gamma\,e\,\tau$ (short-dashed gold), $J\psi \to \gamma\,e\,\mu$ (dotted red), $\psi(2S) \to \gamma\,e\,\mu$ (dot-dashed green)

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Why is $L_G \sim 1/\Lambda^2$ and not $1/\Lambda^3$?

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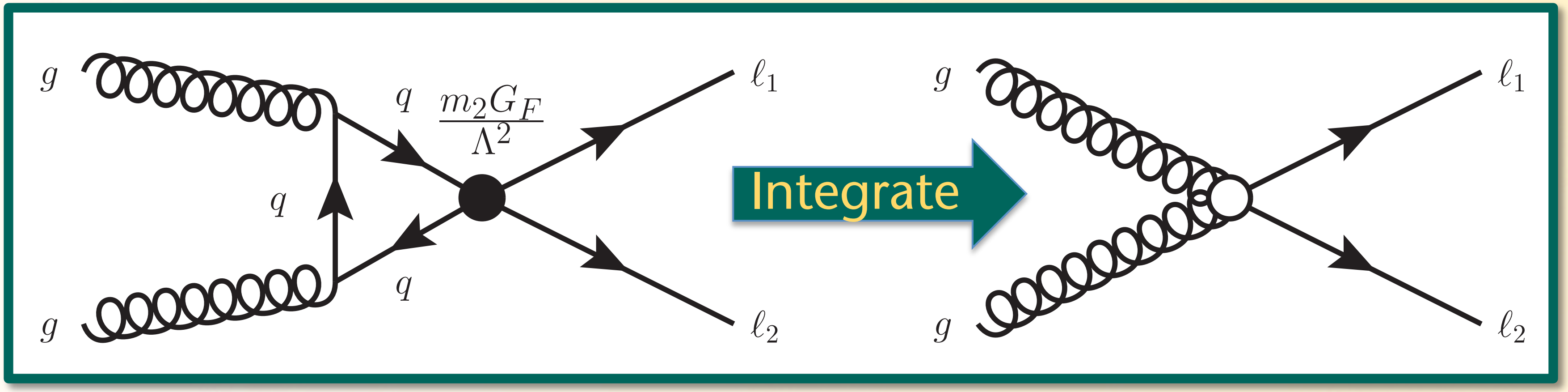

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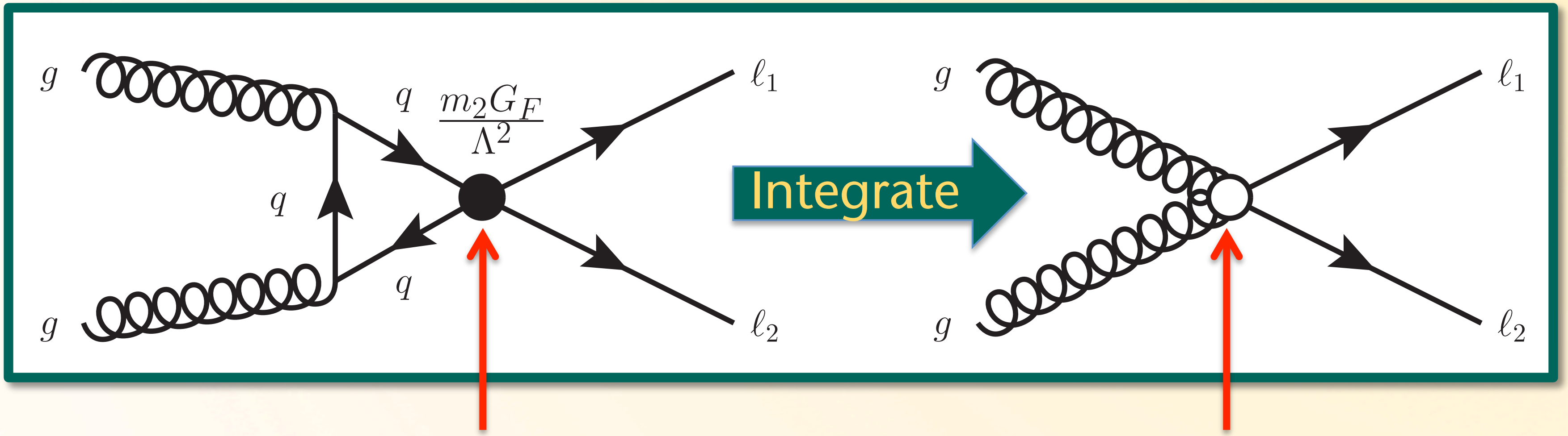

4-fermion operators ~ m_2G_F/Λ^2

Gluonic operators ~ m_2G_F/Λ^2