Search for new physics signal in rare decays of heavy baryon

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Outline

- Motivation / new physics intro.
- Hadronic calculation / QCD factorization
- $\Lambda_b \to K(\pi) l$ decays
- Invisible / semi-invisible decays of Λ_b
- Summary

Motivation

Sakharov: C and CP violation, the baryon number violation are needed to explain the matter-antimatter asymmetry in the Universe.

Experimentally, baryon number violation couplings are searched

$p \to e^+\pi^0$: Super Kamiokande, proton lifetime $\tau > 8.2\times 10^{33}$ y

$p \to K^+\bar{\nu}$: Juno exp., proton lifetime $\tau > 5.9\times 10^{33}$年

$D^0 \to pe^-$: BESIII col, $\mathrm{Br}(D^0 \to pe^-) < 2.2\times 10^{-6}$

$B^0 \to \Lambda e^-$: BaBar col, $\mathrm{Br}(D^0 \to pe^-) < 1.2\times 10^{-8}$

$B \to p\mu^-$: LHCb col , $\mathrm{Br}(B \to p\mu^-) < 2.6\times 10^{-9}$

$\Lambda_b \to K^+\mu^-$: LHCb col, $\mathrm{Br}(\Lambda_b \to K^+\mu^-) < 1.95\times 10^{-9}$

$B^+ \to \psi_D p$: BaBar col, $\mathrm{Br}(B^+ \to \psi_D p) < 10^{-7} \sim 10^{-5}$

Accelerator exp.

Model of baryon number violation

SU(5) grand unification, **Supersymmetry, B -Mesogenesis . ...**

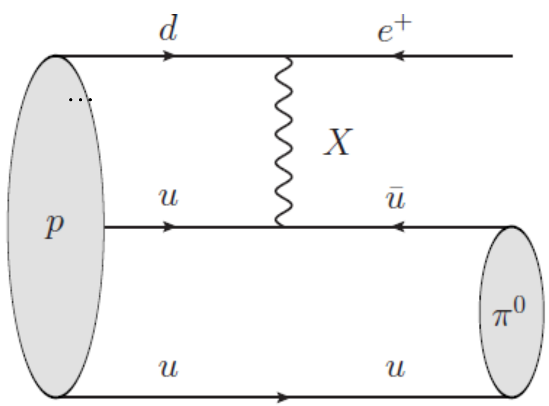
Proton decay $p \to e^+\pi^0$ Lagrangian:

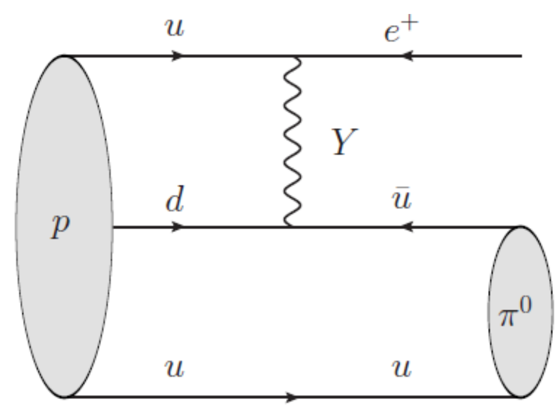
$$\mathcal{L}_i^{\mathrm{GUT}} = \frac{1}{\sqrt{2}} g X_{i,\mu}^{-} \left(-\bar{d}_{i,R}\gamma^\mu e_R^+ + \epsilon_{ijk}\bar{u}_{k,L}^c \gamma^\mu u_{j,L} + \bar{d}_{i,L}\gamma^\mu e_L^+ \right)$$
$$+ \frac{1}{\sqrt{2}} g Y_{i,\mu}^{-} \left(-\bar{d}_{i,R}\gamma^\mu \nu_{e,R}^c + \epsilon_{ijk}\bar{u}_{k,L}^c \gamma^\mu d_{j,L} + \bar{u}_{i,L}\gamma^\mu e_L^+ \right) + h.c.$$

Feynman diagrams

of $p \to e^+\pi^0$

Spectator emission





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Feynman diagrams

of $\Lambda_b \to K(\pi) l$

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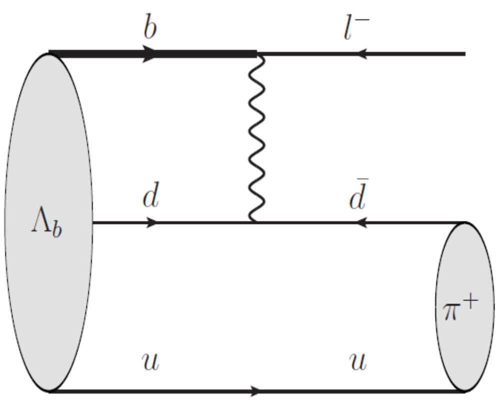
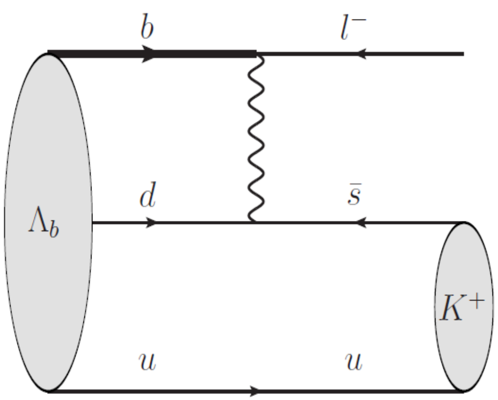




Model independent Leptoquark operators

Effective Hamiltonian at m_b scale after integration of new physics

$$O_1 = \epsilon^{ijk}(\bar{d}_j^c \Gamma b_i)(\bar{\ell}\Gamma s_k), \qquad O_2 = \epsilon^{ijk}(\bar{s}_i^c \Gamma b_j)(\bar{\ell}\Gamma d_k),$$

$$O_3 = \epsilon^{ijk}(\bar{d}_i^c \Gamma s_j)(\bar{\ell}\Gamma b_k), \qquad O_4 = \epsilon^{ijk}(\bar{d}_i^c \Gamma b_j)(\bar{\ell}\Gamma d_k),$$

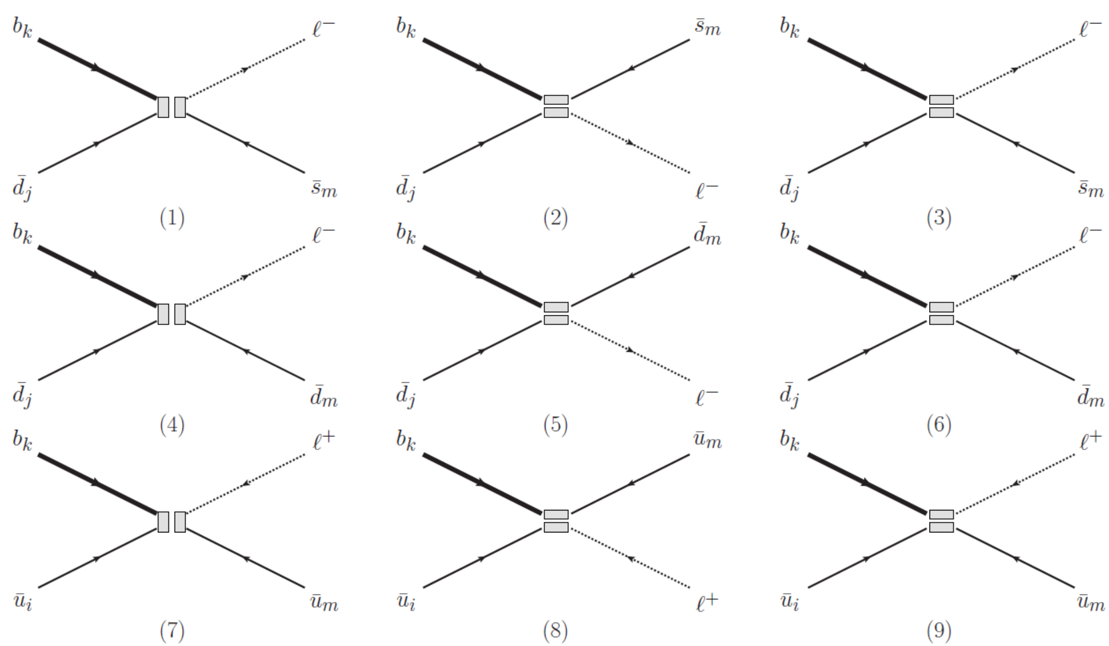
$$O_5 = \epsilon^{ijk}(\bar{d}_i^c \Gamma d_j)(\bar{\ell}\Gamma b_k), \qquad O_6 = \epsilon^{ijk}(\bar{u}_i^c \Gamma b_j)(\bar{u}_k^c \Gamma \ell),$$

$$O_7 = \epsilon^{ijk}(\bar{u}_j^c \Gamma u_i)(\bar{b}_k^c \Gamma \ell),$$

$$\mathcal{H}_{new} = \sum_{\alpha=1}^{7} G_{new,\alpha} O_\alpha,$$

where

$$\Gamma = \{1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\},$$



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$$\mathcal{H}_{new} = \sum_{\alpha=1}^{7} G_{new,\alpha} O_\alpha,$$

$\Delta(B-L) = 2$

$\Lambda_b \to K^+ l^-$: $O_1 \sim O_3$

$\Lambda_b \to \pi^+ l^-$: $O_4 \sim O_5$

Leptoquark operators of $\Lambda_b \to P\, l$, $P=\pi, K$ decay

$\Delta(B-L) = 0$ (GUT)

$\Lambda_b \to \pi^- l^+$: $O_6 \sim O_7$

b decays: The multi-scale problem

NP scale	EW scale	Heavy quark scale	Intermediate scale	Hadronization scale
TeV or beyond	m_W	$m_b(m_c)$	$\sqrt{m_b\Lambda}, m_c$	Λ
$\mathcal{L}_{NP}$	$\mathcal{L}_{SM}+$ $\mathcal{L}_{D>4}$	$\sum_i C_i O_i+$ $\sum_i C_i' O_i'$	SCET-I	Low energy QCD HQET, SCET-II

$$\langle f|\mathcal{H}_{eff}|B\rangle = \mathcal{A}_{\mathrm{F}} + O\left(\frac{\Lambda}{m_b}, \alpha_s\right)$$

- **Perturbation: matching, resummation, evolution**
- **Nonperturbation: Lattice simulation, sum rules…**

Parametrization of form factors

Hadronic Form factor definition of Leptoquark operators O_α

$\Delta(\mathrm{B}-\mathrm{L}) = 2$: $\langle P^+(p)|O_\alpha|\Lambda_b(p_{\Lambda_b})\rangle = [\,A^+ + B^+\,\not{p} + C^+\,\not{q}\,]\,u_{\Lambda_b}(p_{\Lambda_b}),\qquad \alpha = 1\sim 5,$

$\Delta(\mathrm{B}-\mathrm{L}) = 0$: $\langle P^-(p)|O_\alpha|\Lambda_b(p_{\Lambda_b})\rangle = u^T_{\Lambda_b}(p_{\Lambda_b})\,C\,[\,A^- + B^-\,\not{p} + C^-\,\not{q}\,],\qquad \alpha = 6\sim 7.$

Equation of motion $\not{p}_{\Lambda_b} u(p_{\Lambda_b}) = m_{\Lambda_b} u(p_{\Lambda_b})$

Momentum conservation $p_{\Lambda_b} = p + q$

A term can be expressed as combination of B and C terms

$$\not{p}_{\Lambda_b} u_{\Lambda_b}(p_{\Lambda_b}) = (\not{p} + \not{q})u_{\Lambda_b}(p_{\Lambda_b}) = m_{\Lambda_b} u_{\Lambda_b}(p_{\Lambda_b})$$

$$A^\pm u_{\Lambda_b}(p_{\Lambda_b}) = \frac{A^\pm}{m_{\Lambda_b}}\not{p}_{\Lambda_b} u_{\Lambda_b}(p_{\Lambda_b}) = \frac{A^\pm}{m_{\Lambda_b}}(\not{p} + \not{q})u_{\Lambda_b}(p_{\Lambda_b})$$

Form factors at leading order

Equation of motion $\not{q}\, u_\ell(q) = 0$

At leading order, there is only one Lorentz structure contributing to $\boldsymbol{\Lambda_b \to Pl}$ decay

$$\langle P^+(p)\ell^-(q)|O_\alpha|\Lambda_b(p_{\Lambda_b})\rangle \sim \zeta_{\Lambda_b\to P^+}\, \bar{u}_\ell(q)\, \frac{\not{n}}{2}\, u_{\Lambda_b}(p_{\Lambda_b}), \qquad \alpha = 1 \sim 5,$$

$$\langle P^-(p)\ell^+(q)|O_\alpha|\Lambda_b(p_{\Lambda_b})\rangle \sim \zeta_{\Lambda_b\to P^-}\, u^T_{\Lambda_b}(p_{\Lambda_b})\, C\, \frac{\not{n}}{2}\, v_\ell(q), \qquad \alpha = 6 \sim 7,$$

Leading-twist wave function of $\boldsymbol{\Lambda_b^-}$ baryon：

$$\langle 0|\,[u_i(t_1 n)]_A\,[0,t_1 n]\,[d_j(t_2 n)]_B\,[0,t_2 n]\,[h_{v,k}(0)]_C\,|\Lambda_b(v)\rangle$$
$$= \frac{\epsilon_{ijk}}{4N_c!}\, f^{(2)}_{\Lambda_b}(\mu)\,[u_{\Lambda_b}(v)]_C \left[\frac{\not{\bar{n}}}{2}\,\gamma_5\, C^T\right]_{BA} \int_0^\infty d\omega\,\omega \int_0^1 dy\, e^{-i\omega(t_1 y + i t_2 \bar{y})}\, \psi_2(y,\omega)$$

Hadron wave function

LCDA **of Λ_b** baryon: **Exponential** model

$$\psi_2(y,\omega) = y\,(1-y)\,\omega^2\,\frac{1}{\omega_0^4}\,e^{-\omega/\omega_0}$$

Leading-twist wave function of pseudo-scalar meson

$$\langle P(p)|\,[\bar{q}(t\bar{n})]_A\,[t\bar{n},0]\,[q(0)]_B\,|0\rangle = \frac{i f_P}{4}\,\bar{n}\cdot p\left[\frac{\not{n}}{2}\,\gamma_5\right]_{BA}\int_0^1 dx\, e^{ixt\bar{n}\cdot p}\,\phi_P(x,\mu),$$

LCDA **of pseudo-scalar meson $P=\pi$, K :**

$$\phi_P(x,\mu) = 6\,x\,\bar{x}\left[1+\sum_{n=1}^{\infty} a_n^P(\mu)\,C_n^{(3/2)}(2x-1)\right].$$

Form factors calculated in QCD factorization

$$\zeta^a_{\Lambda_b\to P^\pm} = f_P f^{(2)}_{\Lambda_b} \int_0^1 dx \int_0^\infty d\omega\,\omega \int_0^1 dy\, C^a_\pm(x,y,\omega,\mu)\mathcal{J}^a_\pm(x,y,\omega,\mu)\phi_P(x,\mu_0)\psi_2(y,\omega).$$

Jet function: $\mathcal{J}^a_+(x,y,\omega,\mu) = \frac{\pi\,\alpha_s(\mu)\,T^a_c}{4\,\bar{n}\cdot p}\frac{1}{x\,y\,\omega^2}, \qquad \mathcal{J}^a_-(x,y,\omega,\mu) = \frac{\pi\,\alpha_s(\mu)\,T^a_c}{4\,\bar{n}\cdot p}\frac{1}{x\,\bar{y}\,\omega^2},$

SU(3) flavor symmetry at heavy quark limit:

$$\int_0^1 dy\,\mathcal{J}^a_+(x,y,\omega,\mu)\,\psi_2(y,\omega) \sim \int_0^1 dy\,\bar{y} \qquad \int_0^1 dy\,\mathcal{J}^a_-(x,y,\omega,\mu)\,\psi_2(y,\omega) \sim \int_0^1 dy\,y$$

There is only one independent form factor for $\Delta(B-L) = 0$ and $\Delta(B-L) = 2$ decays

$$\zeta^a_{\Lambda_b\to P} = \zeta^a_{\Lambda_b\to P^\pm}.$$

QCD factorization

di-quark behavior in baryon decay

Leptoquark operator

Jet function at endpoint:

$$\mathcal{J}_{+}^{a}(x,y,\omega,\mu) \sim 1/(xy\omega^2)$$

$$\mathcal{J}_{-}^{a}(x,y,\omega,\mu) \sim 1/(x\bar{y}\omega^2)$$

Endpoint behavior of pseudo-scalar and baryon wave function:

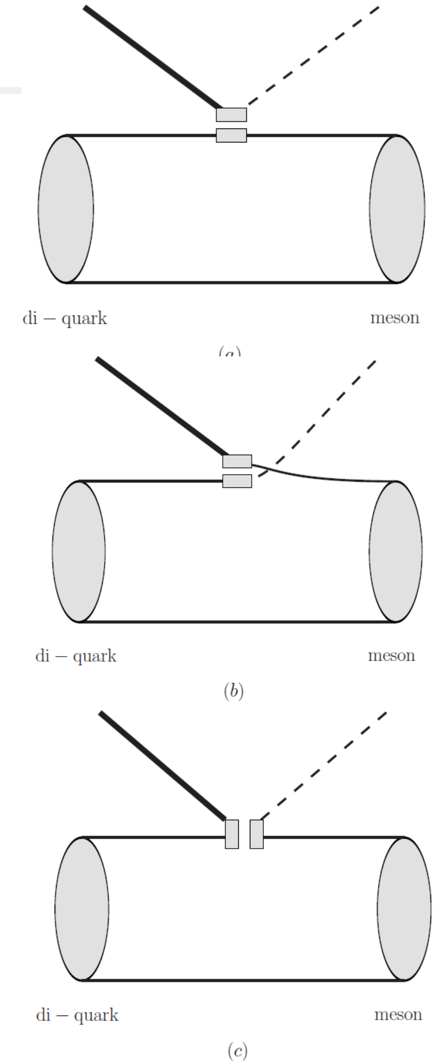
$$\phi_P \overset{x\to 0}{\sim} x, \qquad \psi_2 \overset{y\to 0,\omega\to 0}{\sim} y\omega^2, \qquad \psi_2 \overset{y\to 1,\omega\to 0}{\sim} \bar{y}\omega^2$$

No endpoint divergence in baryon decays

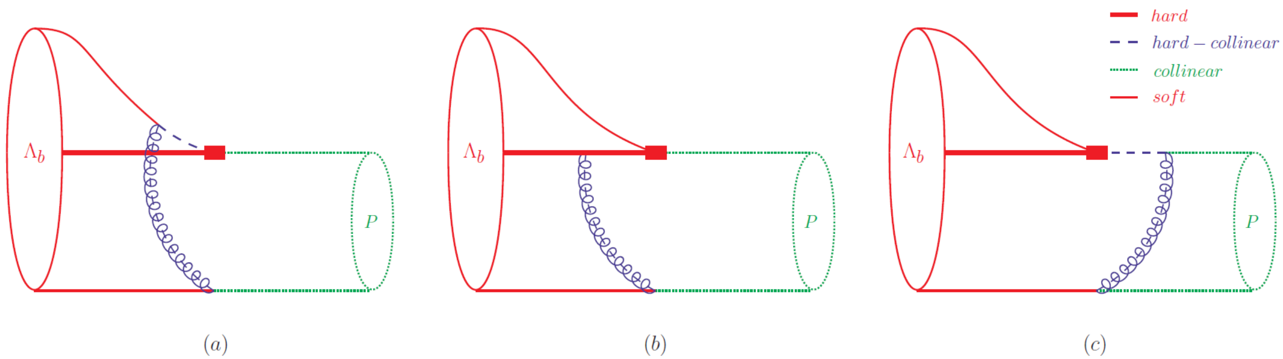
O_3, O_5, O_7

O_2, O_5, O_6

O_1, O_4, O_6



Leading order QCD corrections to form factor



Decay amplitude of Feynman diagram (a)

$$\mathcal{A}^a_\alpha(\Lambda_b \to P^+\ell^-) = G_{new,\alpha}\,\zeta^a_{\Lambda_b\to P^+} \times \bar{u}_\ell(q)\,M^a_\alpha\,u_{\Lambda_b}(v), \qquad \alpha = 1 \sim 5,$$
$$\mathcal{A}^a_\alpha(\Lambda_b \to P^-\ell^+) = G_{new,\alpha}\,\zeta^a_{\Lambda_b\to P^-} \times u^T_{\Lambda_b}(v)\,M^a_\alpha\,v_\ell(q), \qquad \alpha = 6 \sim 7.$$

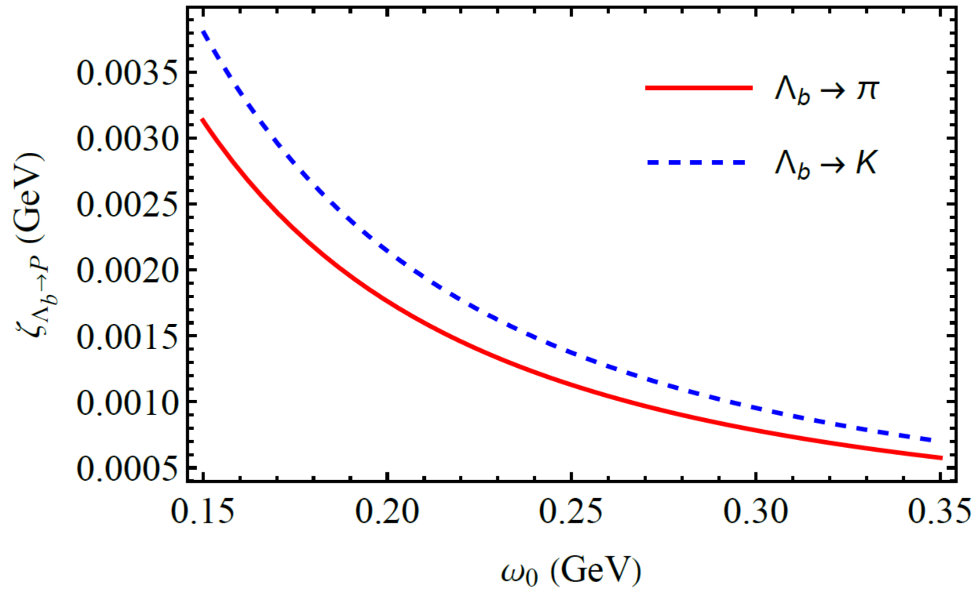
Definition of matrix

$$M^a_1 = -M^a_2 = -M^a_4/2 = -2\,\bar{n}\cdot p\,m^{1/2}_{\Lambda_b}\,\Gamma\,\frac{\not{n}}{2}\,\Gamma, \qquad M^a_3 = M^a_5 = 2\,\bar{n}\cdot p\,m^{1/2}_{\Lambda_b}\,\mathrm{Tr}\left\{\Gamma\,\frac{\not{n}}{2}\right\}\Gamma,$$
$$M^a_6 = 4\,\bar{n}\cdot p\,m^{1/2}_{\Lambda_b}\,\Gamma^T\,C\,\frac{\not{n}}{2}\,\Gamma, \qquad M^a_7 = 2\,\bar{n}\cdot p\,m^{1/2}_{\Lambda_b}\,\mathrm{Tr}\left\{\Gamma\,\frac{\not{n}}{2}\right\}C\,\Gamma,$$

diagram (b) and (c) are suppressed by order Λ_{QCD}/m_b comparing with diagram (a)

Form factor and decay rate

Parameter dependence of form factors



Decay rate as function of new physics parameters

$$\Gamma^{\rm V}_\alpha = \frac{m^3_{\Lambda_b}}{\pi} \left| G_{new,\alpha} \, \zeta_{\Lambda_b \to K} \right|^2, \qquad \alpha = 1 \sim 2,$$

$$\Gamma^{\rm V}_\alpha = \frac{4\, m^3_{\Lambda_b}}{\pi} \left| G_{new,\alpha} \, \zeta_{\Lambda_b \to K} \right|^2, \qquad \alpha = 3,$$

$$\Gamma^{\rm V}_\alpha = \frac{4\, m^3_{\Lambda_b}}{\pi} \left| G_{new,\alpha} \, \zeta_{\Lambda_b \to \pi} \right|^2, \qquad \alpha = 4 \sim 7,$$

$$\Gamma^{\rm S}_\alpha = \Gamma^{\rm P}_\alpha = \frac{1}{4} \Gamma^{\rm A}_\alpha = \frac{m^3_{\Lambda_b}}{4\,\pi} \left| G_{new,\alpha} \, \zeta_{\Lambda_b \to K} \right|^2, \qquad \alpha = 1 \sim 2,$$

$$\Gamma^{\rm S}_\alpha = \Gamma^{\rm P}_\alpha = \frac{1}{4} \Gamma^{\rm A}_\alpha = \frac{m^3_{\Lambda_b}}{\pi} \left| G_{new,\alpha} \, \zeta_{\Lambda_b \to \pi} \right|^2, \qquad \alpha = 4,\ 6.$$

Input parameters

$m_{\Lambda_b} = 5.6196\,\text{GeV}$	$\tau_{\Lambda_b} = 1.471\,\text{ps}$
$\omega_0 = 0.280\,^{+0.047}_{-0.038}\,\text{GeV}$	$f^{(2)}_{\Lambda_b}(\mu_0) = 0.030 \pm 0.005\,\text{GeV}^3$
$f_\pi = 0.1304 \pm 0.0002\,\text{GeV}$	$f_K = 0.1562 \pm 0.0007\,\text{GeV}$
$a_1^\pi(\mu_0) = 0$	$a_2^\pi(\mu_0) = 0.29 \pm 0.08$
$a_1^K(\mu_0) = -0.07 \pm 0.04$	$a_2^K(\mu_0) = 0.24 \pm 0.08$

Numerical results

Numerical results

of $\Lambda_b \to P$ form factors:

$$\zeta_{\Lambda_b \to K} = 1.09^{+0.36}_{-0.42} \times 10^{-3}\,\mathrm{GeV},$$
$$\zeta_{\Lambda_b \to \pi} = 9.00^{+2.92}_{-3.42} \times 10^{-4}\,\mathrm{GeV}.$$

Upper limit of *LHCb* exp. for $\Lambda_b \to K^+\mu^-$:

$$[\mathcal{B}(\Lambda_b \to K^-\mu^+) + \mathcal{B}(\Lambda_b \to K^+\mu^-)] \times \frac{3.1 \times 10^{-6}}{\mathcal{B}(\Lambda_b \to pK^-)}$$
$$< 1.95 \times 10^{-9} \quad \text{at} \quad \mathrm{CL} = 90\,\%.$$

Constraint for new physics couplings from LHCb exp.

$\lvert G_{new,\alpha}\rvert^2$ [GeV^{-4}]	$\Gamma = 1$ or γ_5	$\Gamma = \gamma_\mu$	$\Gamma = \gamma_\mu\gamma_5$	$\Gamma = \sigma_{\mu\nu}$
$\alpha = 1, 2$	$< 5.2 \times 10^{-17}$	$< 1.3 \times 10^{-17}$	$< 1.3 \times 10^{-17}$	-
$\alpha = 3$	-	$< 3.2 \times 10^{-18}$	-	-

There are only vector current contributions from O_3, O_5 and O_7 operator

Extend study to B-Mesogenesis model

B-Mesogenesis model was proposed to simultaneously explain the origins of DM and baryon asymmetry by assuming that dark matter is charged under baryon number

The visible baryon number is violated but the total baryon number is conserved.

dark fermion ψ with baryon number B = −1

$$\mathcal{O}^{L}_{u_a d_b, d_c} = \epsilon_{ijk} \left(\bar{u}^{i,C}_{La} \, d^{j}_{Lb} \right) \left(\bar{\psi}^{C} \, d^{k}_{Rc} \right),$$

$$\bar{\mathcal{O}}^{L}_{u_a d_b, d_c} = \epsilon_{ijk} \left(\bar{u}^{i}_{La} \, d^{j,C}_{Lb} \right) \left(\bar{\psi} \, d^{k,C}_{Rc} \right),$$

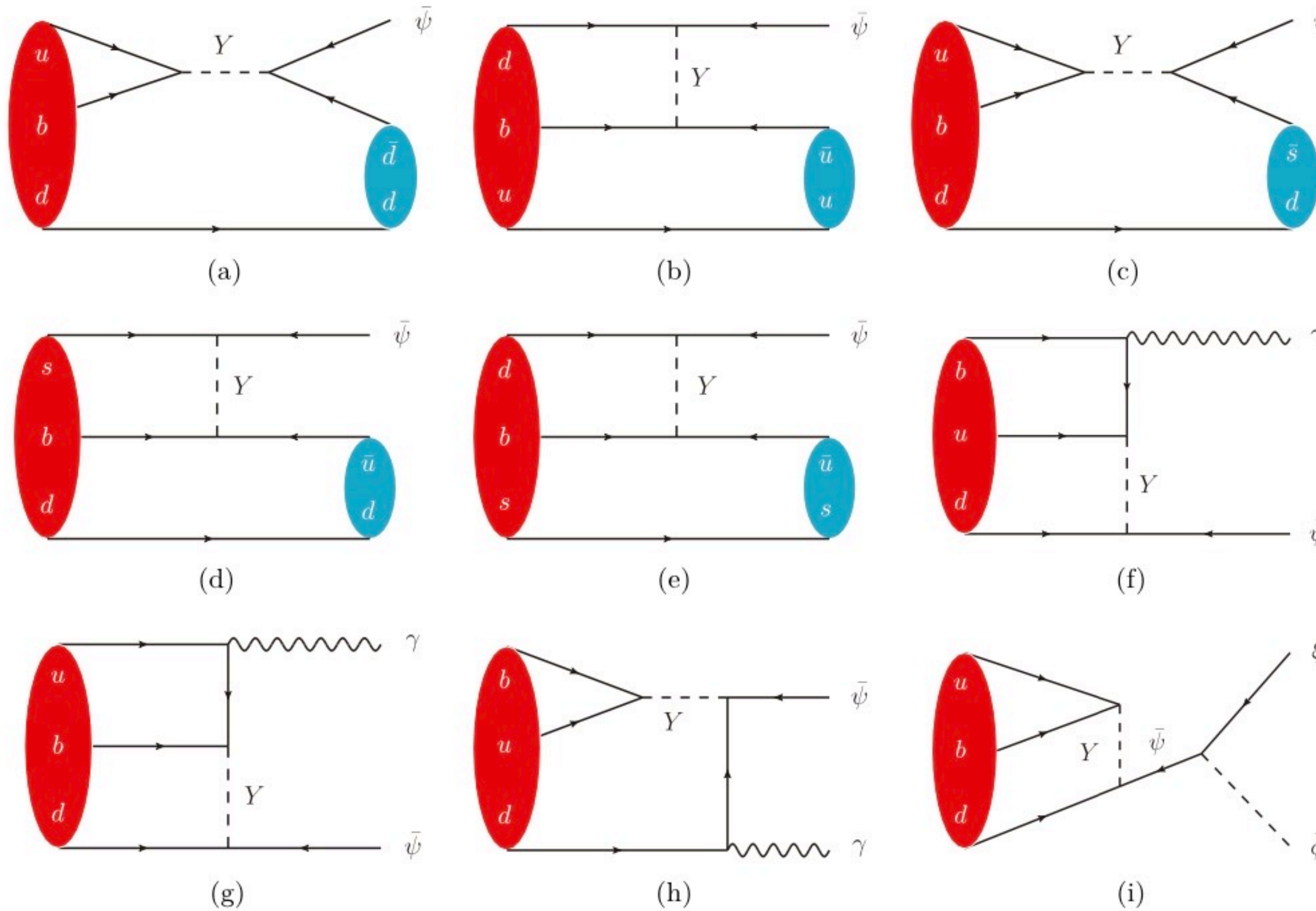
$$\mathcal{O}^{R}_{u_a d_b, d_c} = \epsilon_{ijk} \left(\bar{u}^{i,C}_{Ra} \, d^{j}_{Rb} \right) \left(\bar{\psi}^{C} \, d^{k}_{Rc} \right),$$

$$\bar{\mathcal{O}}^{R}_{u_a d_b, d_c} = \epsilon_{ijk} \left(\bar{u}^{i}_{Ra} \, d^{j,C}_{Rb} \right) \left(\bar{\psi} \, d^{k,C}_{Rc} \right).$$

Extend study to B-Mesogenesis

Decay $\Lambda_b^0 \to P^0\bar{\psi}, \quad \Xi_b^- \to P^-\bar{\psi}, \quad \Lambda_b^0 \to \gamma\bar{\psi}, \quad \Lambda_b^0 \to \xi\bar{\phi}.$

Try to explain dark matter at the universe



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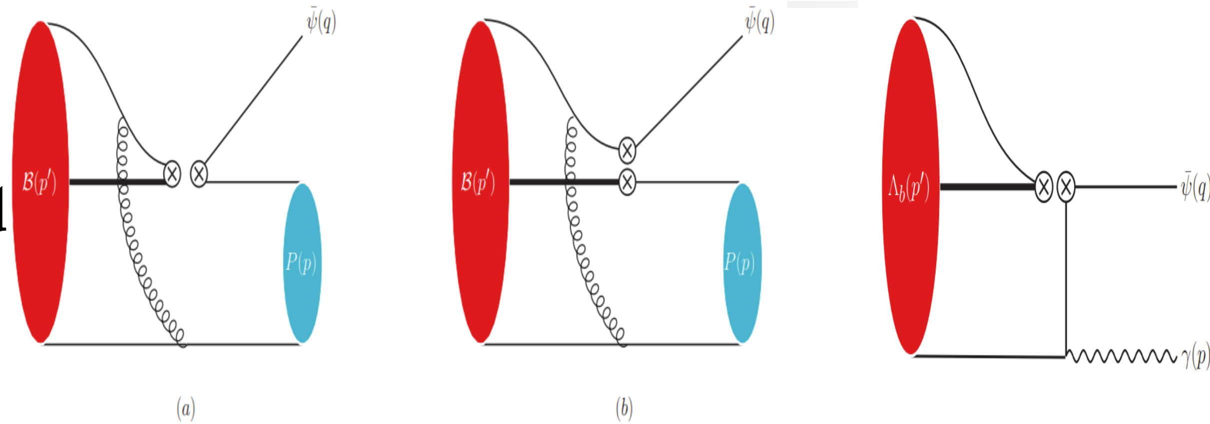
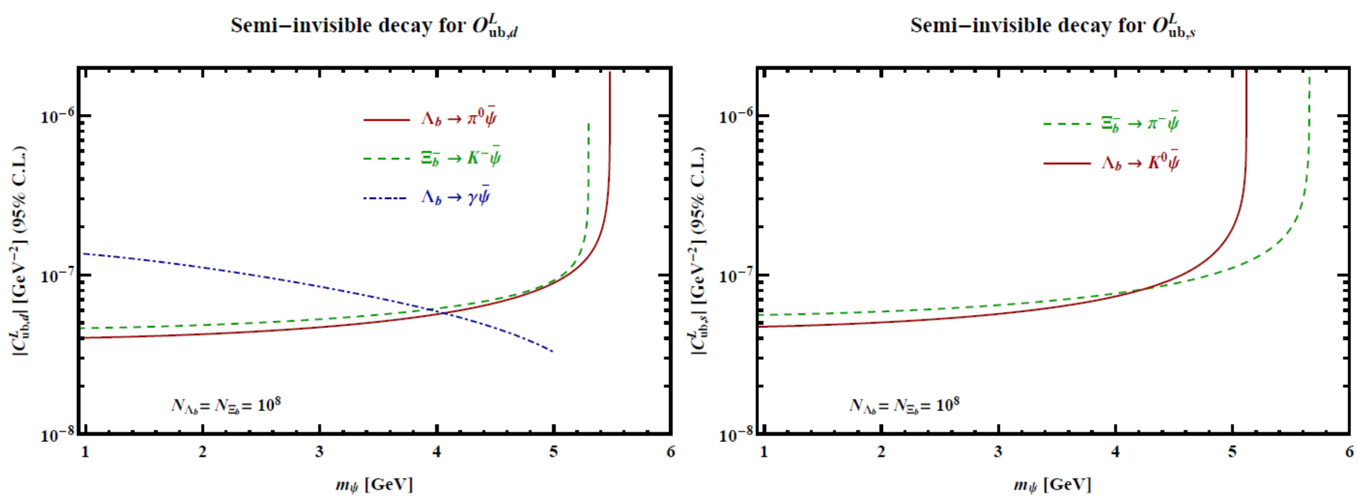
Extend study to B-Mesogenesis

The same form factors calculated as semi-leptonic decay



Possible Constraints can be derived from future experiments



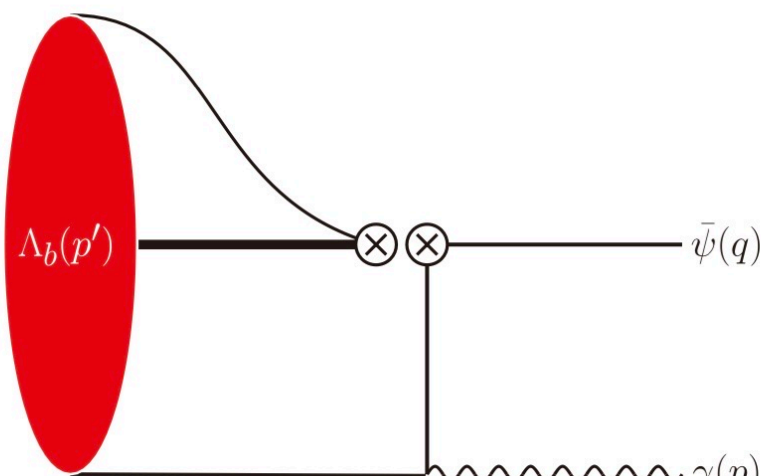
Radiative semi-invisible decay of $\Lambda_b \to \gamma\, \psi$

The decay amplitude is given as

$$i\mathcal{M} = C^{L}_{ub,d}\bar{v}^{C}_{\psi}(q)P_R\left(\zeta_u^{\Lambda_b^0\to\gamma}\frac{\bar{\not n}}{2}\not\epsilon\frac{\not n}{2} + \zeta_d^{\Lambda_b^0\to\gamma}\frac{\not n}{2}\not\epsilon\frac{\bar{\not n}}{2}\right)u_{\Lambda_b}(p'),$$

The hadronic matrix elements can be parameterized in terms of two form factors:

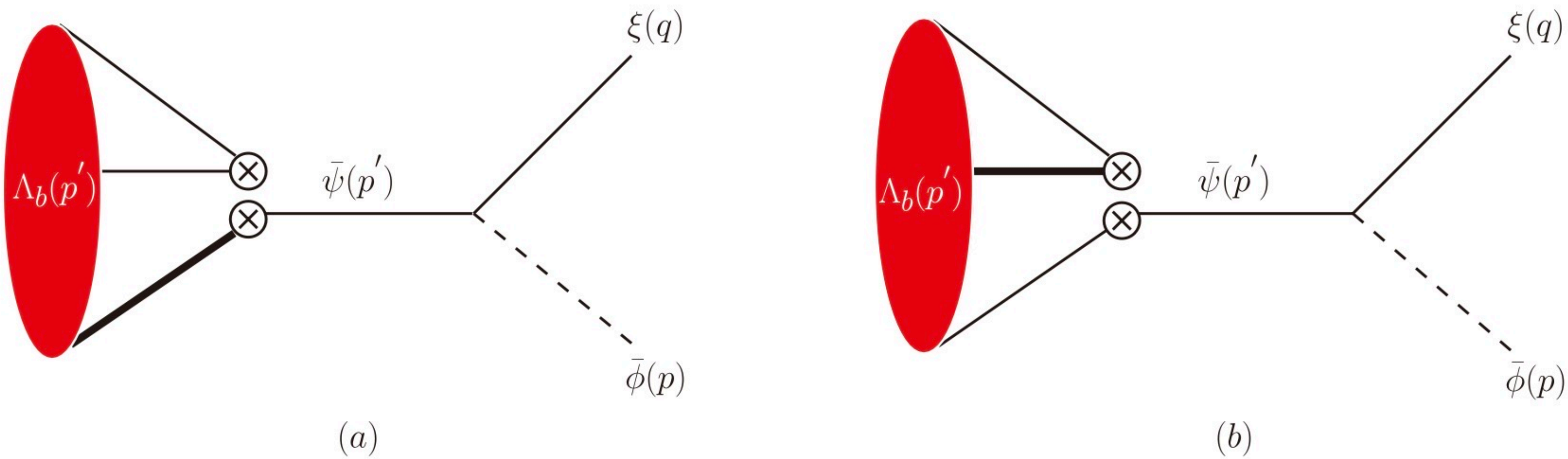
$$\langle\gamma(p)|O'^{L}_{u_a d_b, d_c}|\Lambda_b^0(p')\rangle = P_R\left(\zeta_1^{\Lambda_b\to\gamma}(q^2)\frac{\not p'}{m^2_{\Lambda_b}}i\sigma^{\mu\nu} + \zeta_2^{\Lambda_b\to\gamma}(q^2)\frac{\not q}{m^2_{\Lambda_b}}i\sigma^{\mu\nu}\right)u_{\Lambda_b}(p')\epsilon^*_\mu p'_\nu.$$



Fully invisible decay for Λ_b

In B-Mesogenesis model, the dark fermion ψ should decay into a dark Majorana fermion ξ and a dark scalar baryon ϕ

In this case, we can have Fully invisible decay for Λ_b , unfortunately this decay is difficult for exp. to identify.



Summary/Challenges

- Rich physics, b baryon decays, especially in the search for new physics signal

- Factorization works well in b baryon decays even in collinear factorization.

- Precision study needed in both experimental and theoretical researches

Thanks