Rare radiative baryon decays at LHCb

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on behalf of the LHCb Collaboration

11$^{\text{th}}$ workshop on
Implications of LHCb measurements and future prospects

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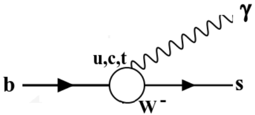
Introduction: Theoretical motivation

The $b \to s\gamma$ process is forbidden at tree level in the Standard Model (SM).
Indirect searches grant access to larger energy scales than direct ones.
At LO in SM only O_7 and O_7' contribute



$$\mathcal{H}_{eff} = -4\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb}(\underbrace{C_7 O_7}_{\text{left}} + \underbrace{C_7' O_7'}_{\text{right}})$$

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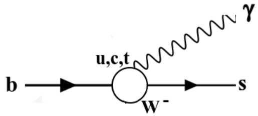

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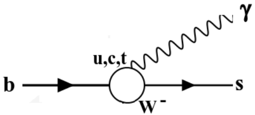
Wilson coefficient can be constrained through measurement of:

- Branching ratio: $\mathcal{B}_{\text{rad}} \propto |C_7|^2 + |C_7'|^2$
- Photon polarization: $\alpha_\gamma{}^{LO} = \frac{1-|\frac{C_7'}{C_7}|^2}{1+|\frac{C_7'}{C_7}|^2}$
- CP asymmetry: $A_{CP} \propto Im\frac{C_7 C_7'}{|C_7|^2+|C_7'|^2}$

Introduction: Theoretical motivation

Photons in such transitions are mainly **left-handed in the SM** since the W boson couples to left-handed quarks [PRL79(1997)185].



$$\mathcal{H}_{eff} = -4\frac{G_F}{\sqrt{2}} V_{ts}^{*} V_{tb} \big(\underbrace{C_7 O_7}_{\text{left}} + \underbrace{\cancelto{\sim 0}{C_7' O_7'}}_{\text{right}} \big)$$

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- Branching ratio: $\mathcal{B}_{\text{rad}} \propto |C_7|^2 + \cancelto{\sim 0}{|C_7'|^2} \propto |C_7|^2$
- Photon polarization: $\alpha_\gamma{}^{LO} = \dfrac{1 - \cancelto{\sim 0}{|\frac{C_7'}{C_7}|^2}}{1 + \cancelto{\sim 0}{|\frac{C_7'}{C_7}|^2}} \sim 1$
- CP asymmetry: $A_{CP} \propto Im \cancelto{\sim 0}{\dfrac{C_7 C_7'}{|C_7|^2 + |C_7'|^2}} \sim 0$

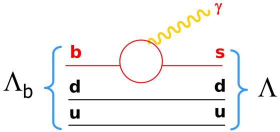
Baryon decays

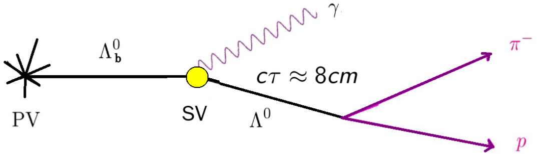
Radiative b-baryon decays:

- Non-zero spin grants access to more observables [JPG24(1998)979, EPJC79(2019)634]
- Two spectator quarks $\Longrightarrow$ different form factors
- Photon polarization has never been measured!!
- *b*-baryons only at accesible *pp* colliders (LHC)

Caveats:

- Challenging reconstruction at LHCb
  - No photon direction and long-lived particle $\Longrightarrow$ No secondary vertex.
- Uncertainty on b-baryon fragmentation fractions higher than for b-mesons
  - $\sigma\left(\frac{f_s}{f_u+f_d}\right) \sim 0.006 \quad \sigma\left(\frac{f_{\Lambda_b}}{f_u+f_d}\right) \sim 0.018 \quad \sigma\left(\frac{f_{\Xi_b}}{f_{\Lambda_b}}\right) \sim 0.027$
    [PRD104(2021)032005, PRD99(2019)052006]



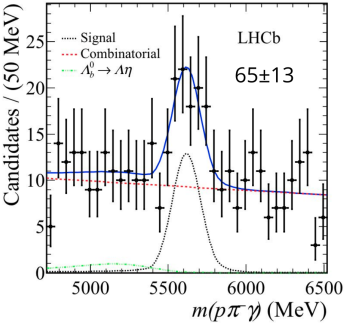


Photon polarization in $\Lambda_b^0 \to \Lambda\gamma$

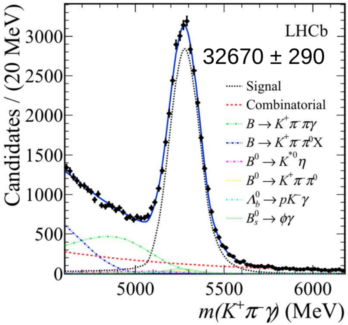
$\Lambda_b^0 \to \Lambda\gamma$ decay channel recently observed (1.6 fb^{-1}) [PRL123(2019)031801]:

- $\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$
- Opens the possibility for direct measurement of photon polarization (α_γ) in b-baryon decays

$\Lambda_b^0 \to \Lambda\gamma$



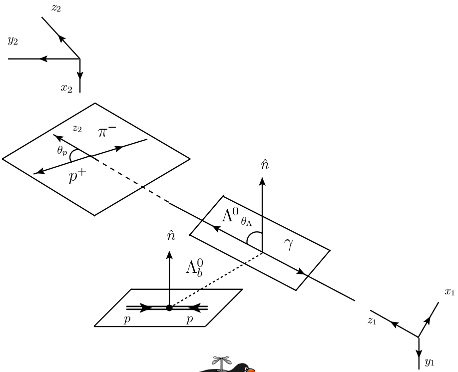
$B^0 \to K^*\gamma$



Photon polarization in $\Lambda_b^0 \to \Lambda\gamma$ [LHCb-PAPER-2021-03]

- First angular analysis of radiative b-baryon decays
- Using 6fb^{-1} collected by LHCb
- Angular distribution and sensitivity studies computed [EPJC79(2019)634]

$$\Gamma_{\Lambda_b}(\theta_\gamma, \theta_p) = 1 - \alpha_\Lambda P_{\Lambda_b} \cos\theta_p \cos\theta_\gamma - \boldsymbol{\alpha_\gamma}\left(\alpha_\Lambda \cos\theta_p - P_{\Lambda_b}\cos\theta_\gamma\right)$$



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Integrating in helicity angles:

$$\Gamma_{\Lambda_b}(\theta_\gamma) = \frac{1}{4}\left(1 - \boldsymbol{\alpha_\gamma} P_{\Lambda_b}\cos\theta_\gamma\right)$$

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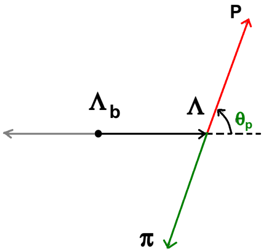

The decay parameters are:

- $P_{\Lambda_b}(13\text{ TeV}) \in [-0.052, 0.091]$ [LHCb: JHEP06(2020)110]
- $\alpha_\Lambda = 0.754 \pm 0.004$ [BESIII: NP15(2019)631–634]

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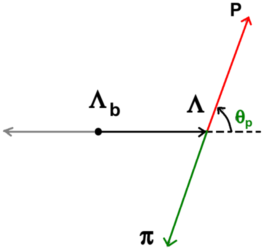

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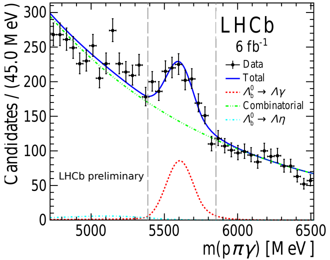
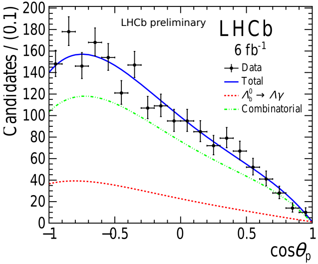
Photon polarization in $\Lambda_b^0 \to \Lambda\gamma$ [LHCb-PAPER-2021-03]

Using events in the signal region: $N_{\Lambda_b^0 \to \Lambda\gamma} = 440 \pm 40$

- Angular fit to $\cos\theta_p$ in the signal region
- Angular acceptance for signal mode from simulation
  - Controlled using $\Lambda_b^0 \to \Lambda J/\psi$
- Angular background from mass side-bands





$$\alpha_\gamma = 0.82 \pm 0.23 \pm 0.13$$

Compatible with the SM prediction ($\alpha_\gamma = 1$)

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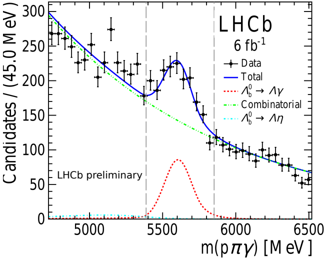
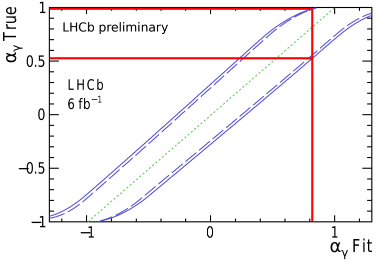




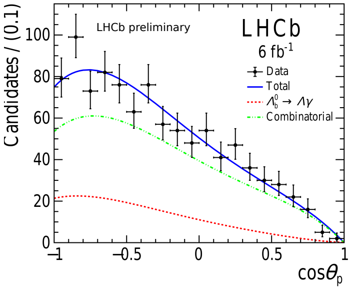
$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\;^{+0.04}_{-0.13}$$

Compatible with the SM prediction ($\alpha_\gamma = 1$)

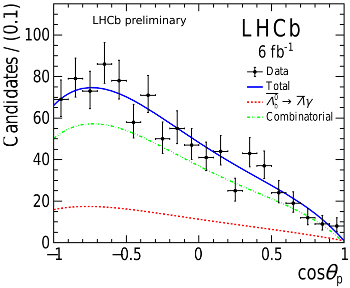
Photon polarization in $\Lambda_b^0 \to \Lambda\gamma$ [LHCb-PAPER-2021-03]

CP test on $\Lambda_b^0 \to \Lambda\gamma$ and $\overline{\Lambda_b^0} \to \overline{\Lambda}\gamma$

$\Lambda_b^0 \to \Lambda\gamma$



$\overline{\Lambda_b^0} \to \overline{\Lambda}\gamma$



- $\alpha_\gamma^{\Lambda_b^0 \to \Lambda\gamma} = 1.26 \pm 0.42 \pm 0.20$
- $\alpha_\gamma^{\overline{\Lambda_b^0} \to \overline{\Lambda}\gamma} = -0.55 \pm 0.32 \pm 0.16$

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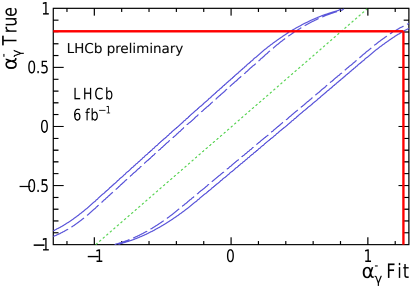
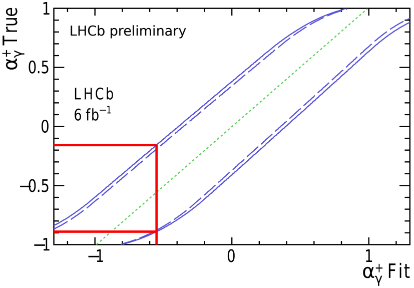


$\overline{\Lambda_b^0} \to \overline{\Lambda}\gamma$

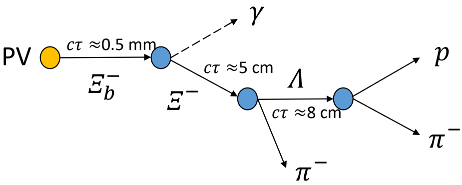


- $\alpha_\gamma^{\Lambda_b^0 \to \Lambda\gamma} > 0.56(0.44)$ at 90% (95%) CL
- $\alpha_\gamma^{\overline{\Lambda_b^0} \to \overline{\Lambda}\gamma} = -0.56^{+0.36}_{-0.33}\,{}^{+0.16}_{-0.09}$

Search for the $\Xi_b^- \to \Xi^- \gamma$ decay [arXiv:2108.07678]

First search of the $\Xi_b^- \to \Xi^- \gamma$ decay

- No previous limit:
  - $\mathcal{B}(\Xi_b^- \to \Xi^- \gamma)_{\text{theo}} = (3.03 \pm 0.10) \times 10^{-4}$ [PRD83('11)054007]
  - $\mathcal{B}(\Xi_b^- \to \Xi^- \gamma)_{\text{theo}} = (1.23 \pm 0.64) \times 10^{-5}$ [arXiv:2008.06624]
- Analysis uses 5.4 fb^{-1} LHCb data
- Normalization channel: $\Xi_b^- \to \Xi^- J/\psi$



First search of the $\Xi_b^- \to \Xi^-\gamma$ decay

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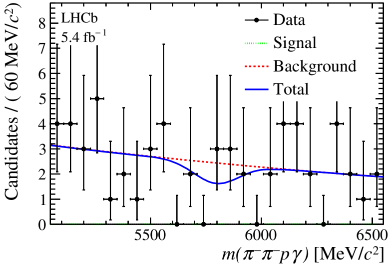
- Analysis uses 5.4 fb^{-1} LHCb data
- Normalization channel: $\Xi_b^- \to \Xi^- J/\psi$
- No $\Xi_b^- \to \Xi^-\gamma$ is found

$\Xi_b^- \to \Xi^-\gamma$



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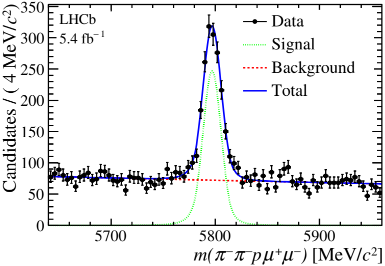
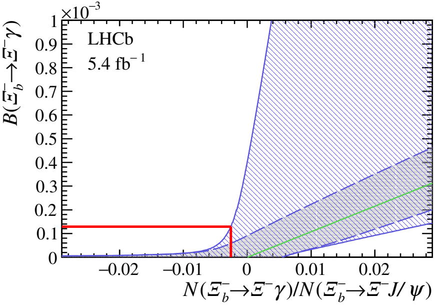


Search for the $\Xi_b^- \to \Xi^- \gamma$ decay [arXiv:2108.07678]

First limit of $\Xi_b^- \to \Xi^- \gamma$ using Feldman Cousin method:



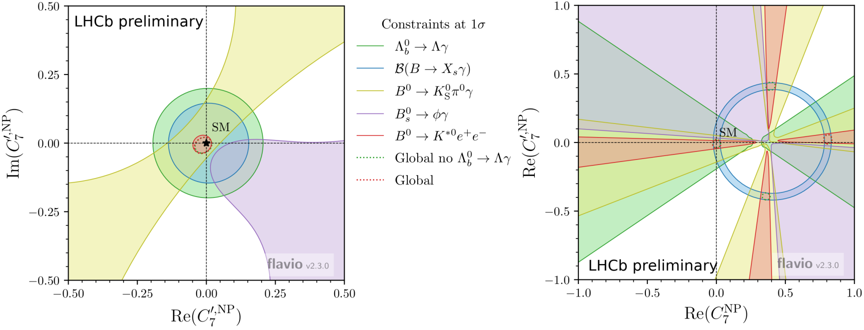
Source	Uncertainty (%)
Mass fit model (signal)	9.1
Mass fit model (background)	7.8
Efficiency ratio	4.6
Hardware trigger	10.0
Simulation/Data agreement	6.0
$\mathcal{B}(\Xi_b^- \to \Xi^- J/\psi)$	**45.6**
Sum in quadrature	48.7

$$\mathcal{B}(\Xi_b^- \to \Xi^- \gamma) < 1.3(0.6) \times 10^{-4} \text{ at } 95\% \text{ } (90\%) \text{ CL}$$

- $\mathcal{B}(\Xi_b^- \to \Xi^- J/\psi)$ is the main source of uncertainty
- Providing also the limit: $\frac{\mathcal{B}(\Xi_b^- \to \Xi^- \gamma)}{\mathcal{B}(\Xi_b^- \to \Xi^- J/\psi)} < 0.12\,(0.08)$ at 95% (90%) CL

NP Constraints

Constraints to C_7' from radiative decays [LHCb-PAPER-2021-03]



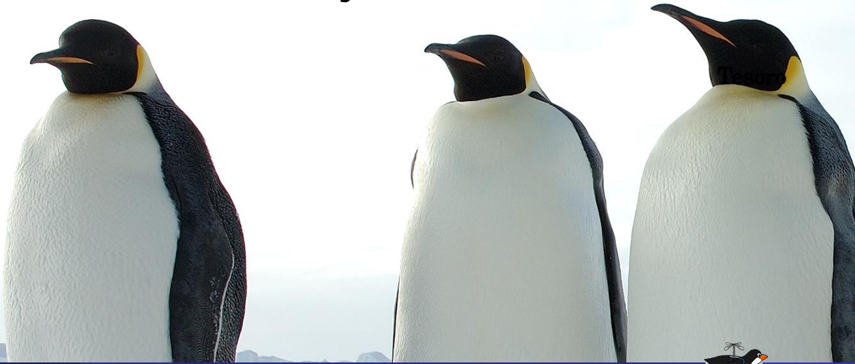
- Results presented are statistically dominated
- Only using α_γ average
  - Allow to discard two regions in the C_7 vs C_7' plane
  - Using $\alpha_\gamma^{\mathrm{CP}}$ could provide further constraints
  - Need phenomenology input

Conclusions

- The radiative transition $b \to s(d)\gamma$ is sensitive to New Physics
  - They are extensively studied at LHCb
  - Different decay modes and observables
  - Strongest constrains to C_7 and C_7'

- LHCb is undergoing a major upgrade
- Expect more precise results from the upcoming LHCb Run 3

Thanks for your attention



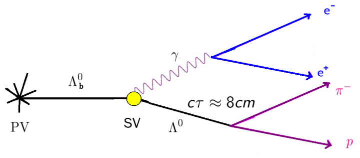
Converted photons

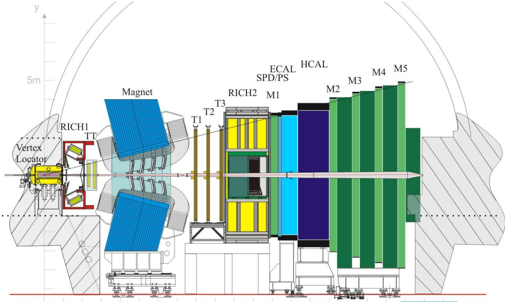
Most of radiative analyses use calorimetric photons

- Converted to a e^+e^- pair after the magnet or unconverted

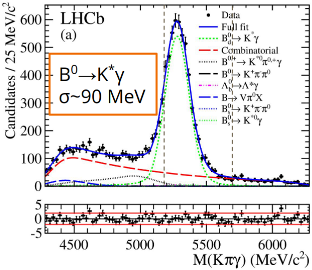
It is also possible to use converted photons ($\gamma \to e^+e^-$):

- e^+e^- track can be reconstructed $\implies$ B mass resolution 3 times better
    - Allow to access $|V_{td}/V_{ts}|$ suppressed modes like $B_s \to K^*\gamma$
- Grant access to SV in decays involving long-lived particles
- Its rate is 20 times lower than for calo photons
- More analyses with converted photons will become feasible with more data

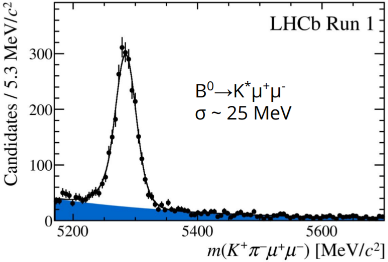




Experimental challenges



[Nucl.Phys.B867(2013)1]



[PRL125(2020)011802]

Challenges for analysis involving neutrals (γ and π^0):

- Photon direction not reconstructed:
  - Mass resolution dominated by photon momentum
  - Large background ($\sim 10\,\gamma$/events, merge $\pi^0 \to \gamma\gamma$)
- Rare decays $\implies$ low signal yield $\left(\mathcal{B} \sim O(10^{-5})\right)$

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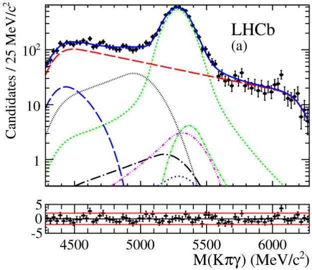

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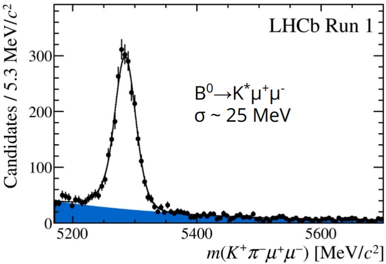

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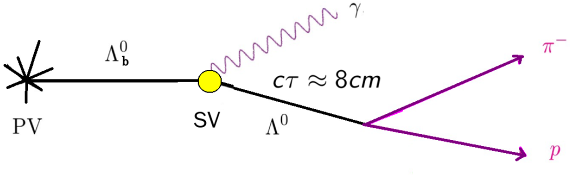

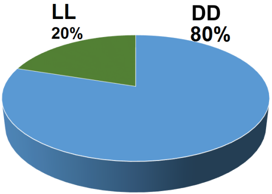

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- Decays involving long-lived particles (K_S, Λ, Ξ^-)
  - Decay after the VELO
    - Worse IP/vertex position resolution
    - Trigger only selects Long tracks
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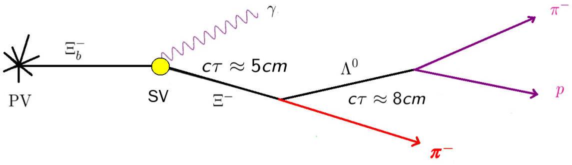

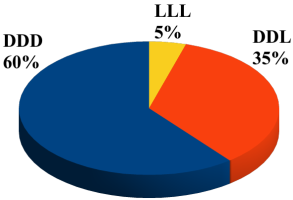

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Why $\Xi_b^- \to \Xi^- J/\psi$ as normalization channel

$$\begin{aligned}
\mathcal{B}(\Xi_b^- \to \Xi^- J/\psi) &= & (4.9 \pm 2.2) \times 10^{-4} \\
\mathcal{B}(\Lambda_b^0 \to \Lambda J/\psi) &= & (3.29 \pm 1.11) \times 10^{-4} \\
\mathcal{B}(\Lambda_b^0 \to p K^- J/\psi) &= & (3.2 \pm 0.6) \times 10^{-4} \\
\frac{f_{\Xi_b}}{f_{\Lambda_b}} &= & (8.2 \pm 2.6) \times 10^{-4}
\end{aligned}$$

$$\begin{aligned}
\mathcal{B}(\Xi_b^- \to \Xi^- \gamma) &\propto \mathcal{B}(\Xi_b^- \to \Xi^- J/\psi) & \Longrightarrow \sigma = 45\% \\
\mathcal{B}(\Xi_b^- \to \Xi^- \gamma) &\propto \frac{1}{f_{\Xi_b}/f_{\Lambda_b}} \mathcal{B}(\Lambda_b^0 \to \Lambda J/\psi) & \Longrightarrow \sigma = 46\% \\
\mathcal{B}(\Xi_b^- \to \Xi^- \gamma) &\propto \frac{1}{f_{\Xi_b}/f_{\Lambda_b}} \mathcal{B}(\Lambda_b^0 \to p K^- J/\psi) & \Longrightarrow \sigma = 37\%
\end{aligned}$$

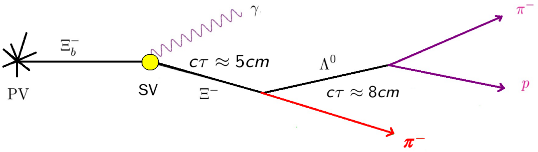
Considering measurement with 20% uncertainty (as $f_{\Lambda_b}\mathcal{B}(\Lambda_b^0 \to \Lambda J/\psi)$)

- When $\mathcal{B}(\Lambda_b^0 \to \Lambda J/\psi)$ is measured by LHCb $\sigma = 37\%$
- When $\mathcal{B}(\Xi_b^- \to \Xi^- J/\psi)$ is measured by LHCb $\sigma = 20\%$

Angular distribution: $\Xi_b^- \to \Xi^- \gamma$

The $\Xi_b^- \to \Xi^- \gamma$ decay is also sensitive to photon polarization through angular distribution [arXiv:1902.04870]:

- Two long-lived particle involved
- Extra decay
- Additional helicity angle



$$\Gamma_{\Xi_b^-}(\theta_\Xi, \theta_\Lambda, \theta_p) \propto 1 + \alpha_\Lambda \alpha_\Xi \cos\theta_p - \alpha_\gamma \alpha_\Xi \cos\theta_\Lambda - \alpha_\gamma \alpha_\Lambda \cos\theta_\Lambda \cos\theta_p$$
$$- P_{\Xi_b} \alpha_\Xi \cos\theta_\Xi \cos\theta_\Lambda + P_{\Xi_b} \alpha_\gamma \alpha_\Xi \alpha_\Lambda \cos\theta_\Xi \cos\theta_p$$
$$- P_{\Xi_b} \alpha_\Lambda \cos\theta_\Xi \cos\theta_\Lambda \cos\theta_p + P_{\Xi_b} \alpha_\gamma \cos\theta_\Xi$$

The values of the decay parameters are:

- $\alpha_\Xi = -0.39 \pm 0.012$ [PDG 2019]
- $\alpha_\Lambda = 0.750 \pm 0.010$ [PDG 2019]

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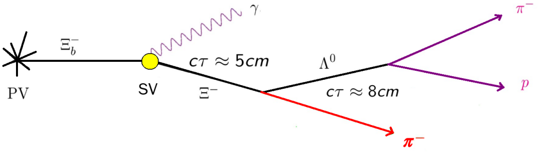

$$\Gamma_{\Xi_b}(\theta_\Lambda, \theta_p) = \frac{1}{4}\left(1 - \boldsymbol{\alpha_\gamma} \alpha_\Xi \cos\theta_\Lambda + \alpha_\Lambda \cos\theta_p \left(\alpha_\Xi - \boldsymbol{\alpha_\gamma} \cos\theta_\Lambda\right)\right)$$

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Radiative decays

How to access **the photon polarization** in *b*-hadron decays?

- **Time dependent analyses, using B-$\overline{\text{B}}$ interference of mixing and decay:**
  - Final common state for neutral B and $\overline{\text{B}}$: $B_{(s)} \rightarrow V\gamma$, $V \rightarrow KK$, $\pi\pi$
  - B_s more profitable $(\Delta\Gamma_s >> \Delta\Gamma_d)$
  - @ LHCb: V to charged tracks, better no π^0's, no K_s's (Ex: $\cancel{B_d \rightarrow K^{*0} (K_s\pi^0)\gamma}$)
  - $B_s \rightarrow \phi\gamma$, $B_d \rightarrow \rho\gamma$, $B_d \rightarrow \omega\gamma$
  - Observables: time dependent decay widths, CP asymmetries
  - Need the use of flavour tagging, which reduces a lot the statistics $(\varepsilon_{eff}$~5%)

- **Angular analyses:**
  - $B_{(s)}$ to three-body + γ decays $(B^+ \rightarrow K^-\pi^+\pi^+\gamma)$
  - Decays of b-baryons ($\Lambda_b \rightarrow \Lambda\gamma$ …)
  - Decays with an electron pair in the final state $\gamma \rightarrow e^-e^+$

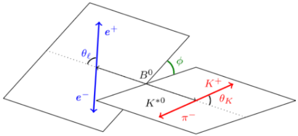
    with γ real: radiative decays with converted photons $(B_{(s)} \rightarrow V\gamma(\rightarrow e^-e^+))$

    or virtual: $B \rightarrow K^*e^+e^-$ analyzed in the low q^2 region

$B \to K^* ee$ at very low q^2

New analysis with 9 fb^{-1} LHCb data [JHEP12(2020)081]:

- Decay is dominated by $b \to s\gamma$ pole at very low q^2 (0.0008 - 0.257 GeV^2)



- Relevant angles: θ_ℓ, θ_K, $\tilde{\phi}$
- Angular observables: F_L, A_T^{Re}, $A_T^{(2)}$, A_T^{Im}
- Sensitive to the polarization of the virtual photon

$$A_{\mathrm{R(L)}} \equiv A_{\mathrm{R(L)}} e^{i\phi_{\mathrm{R(L)}}}, \ \tan\chi \equiv |C_7'/C_7|$$

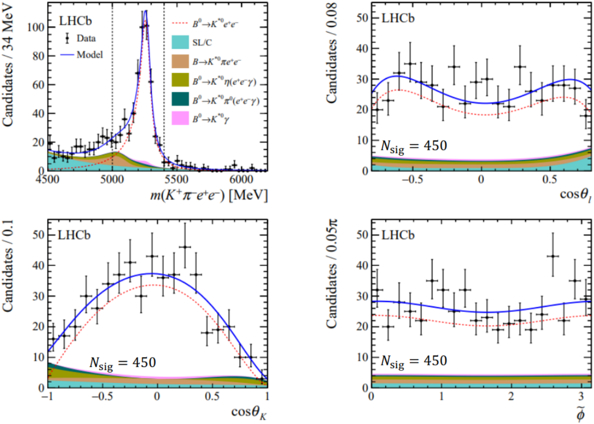
$$A_{\mathrm{T}}^{(2)} \simeq \sin(2\chi)\cos(\phi_{\mathrm{L}} - \phi_{\mathrm{R}}),$$

$$A_{\mathrm{T}}^{\mathrm{Im}} \simeq \sin(2\chi)\sin(\phi_{\mathrm{L}} - \phi_{\mathrm{R}}),$$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} =$$

$$= \frac{9}{16\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos2\theta_\ell - F_{\mathrm{L}}\cos^2\theta_K\cos2\theta_\ell + (1-F_{\mathrm{L}})A_{\mathrm{T}}^{\mathrm{Re}}\sin^2\theta_K\cos\theta_\ell + \frac{1}{2}(1-F_{\mathrm{L}})A_{\mathrm{T}}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos2\tilde{\phi} + \frac{1}{2}(1-F_{\mathrm{L}})A_{\mathrm{T}}^{\mathrm{Im}}\sin^2\theta_K\sin^2\theta_\ell\sin2\tilde{\phi}\Big]$$

$B \to K^{*}ee$ at very low q^2



$$F_{\rm L} = 0.044 \pm 0.026 \pm 0.014,$$
$$A_{\rm T}^{\rm Re} = -0.06 \pm 0.08 \pm 0.02,$$
$$A_{\rm T}^{(2)} = +0.11 \pm 0.10 \pm 0.02,$$
$$A_{\rm T}^{\rm Im} = +0.02 \pm 0.10 \pm 0.01,$$

Uncertainty statistically dominated.

$A_T^{(2)}$ and $A_T^{\rm Im}$ results dominate the senstitivity to Re & Im of $C_7^{(\prime)}$