Radiative *b*-decays at LHCb

EPS-HEP 2021 (Virtual)

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On behalf of the LHCb Collaboration

Today's results

- Measurement of the photon polarization in $\Lambda_b \to \Lambda\,\gamma$ decays
  - LHCb-PAPER-2021-030 (in preparation) **NEW**

- Search for the radiative $\Xi_{\mathrm{b}}^{-} \to \Xi^{-}\,\gamma$ decay
  - LHCb-PAPER-2021-017 (in preparation) **NEW**

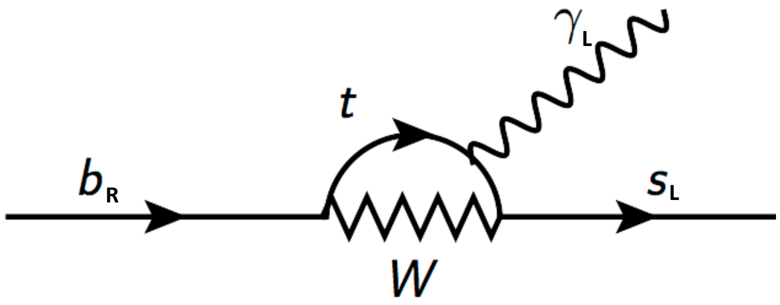
- Strong constraints on the $b \to s\,\gamma$ photon polarization from $B^0 \to K^* e^+ e^-$ decays
  - JHEP 2012 (2020) 081

Radiative b-decays

$b \to s(d)\,\gamma$ are Flavor-Changing-Neutral-Currents (FCNC).

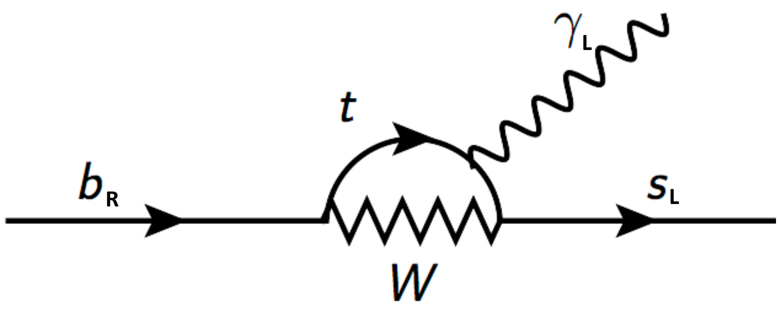
- Forbidden at tree level in Standard Model (SM) → loop diagrams.

- Can probe New Physics at higher energy scales via measurements of angular observables, Branching Ratios (BR), CP asymmetries and the photon polarization.



Radiative b-decays

$\boldsymbol{b \rightarrow s(d)\, \gamma}$ are Flavor-Changing-Neutral-Currents (FCNC).



Effective Hamiltonian

$$\mathcal{H}_{eff} \simeq -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left(\overbrace{\mathcal{C}_7 \mathcal{O}_7}^{\text{left-handed}} + \overbrace{\mathcal{C}_7' \mathcal{O}_7'}^{\text{right-handed}} \right)$$

- Electromagnetic operator $\mathcal{O}_7^{(\prime)}$.
- Wilson coefficients $C_7^{(\prime)}$.

CP Asymmetries

$\mathrm{Im}(\mathrm{C}_7^{(\prime)})$

Branching ratios

$|C_7|^2 + |C_7'|^2$

Photon polarization

$|C_7'/C_7|$

γ mostly left handed in SM

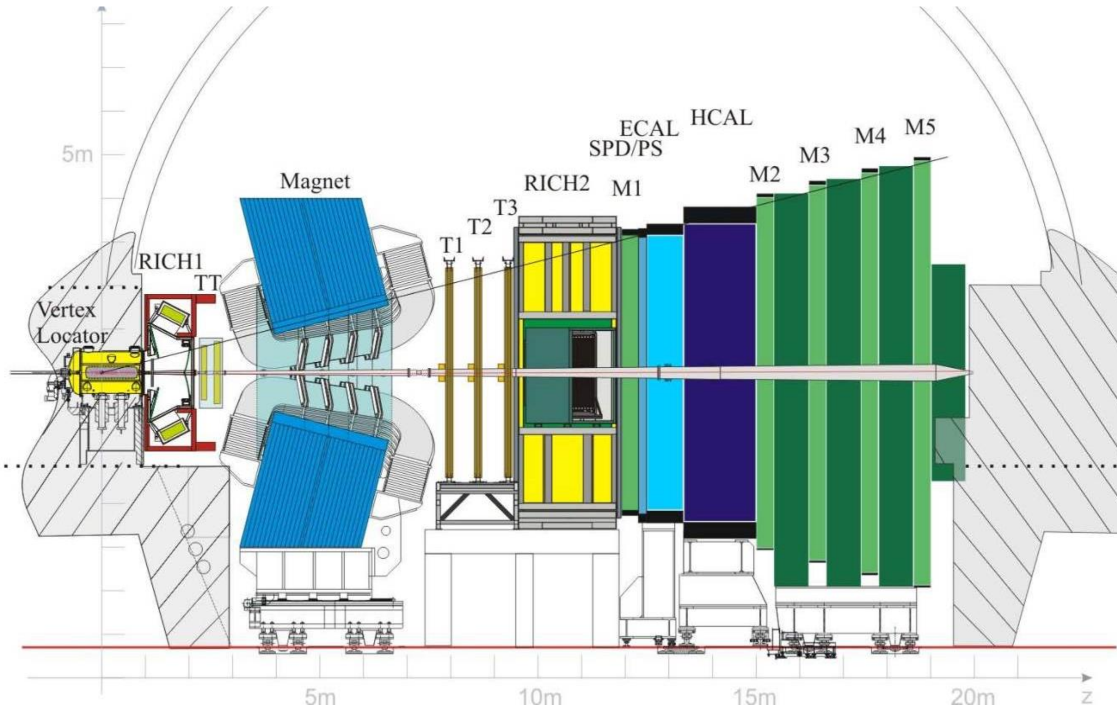
$$\alpha_\gamma = \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R} = \frac{1 - |r|^2}{1 + |r|^2} \sim \mathbf{1}\ (\text{S.M.}) \qquad |r| = \frac{|\mathcal{C}_7'|}{|\mathcal{C}_7|} \simeq \mathcal{O}\left(\frac{m_s}{m_b}\right) \simeq 0.02$$

- Sensitive to right-handed currents (NP).

LHCb detector

Single-arm forward spectrometer to study heavy flavor physics (*b*- and *c*-hadron decays)
Acceptance: $2 < \eta < 5$.

- Momentum resolution 0.4-0.6% at 5-100 GeV
- Kaon ID eff: 95% with 5% $\pi \rightarrow \mathrm{K}$ miss-ID prob.
- Energy resolution for photons:
  $$1\% + 10\%/\sqrt{E(\mathrm{GeV})}$$



[Int. J. Mod. Phys. A 30 (2015) 153022]

Photon polarization in $\Lambda_b \to \Lambda\gamma$ decays

NEW

LHCb-PAPER-2021-030 (in preparation)

Recent observation of $\Lambda_b \to \Lambda\,\gamma$ decay channel. (1.6 fb^{-1})

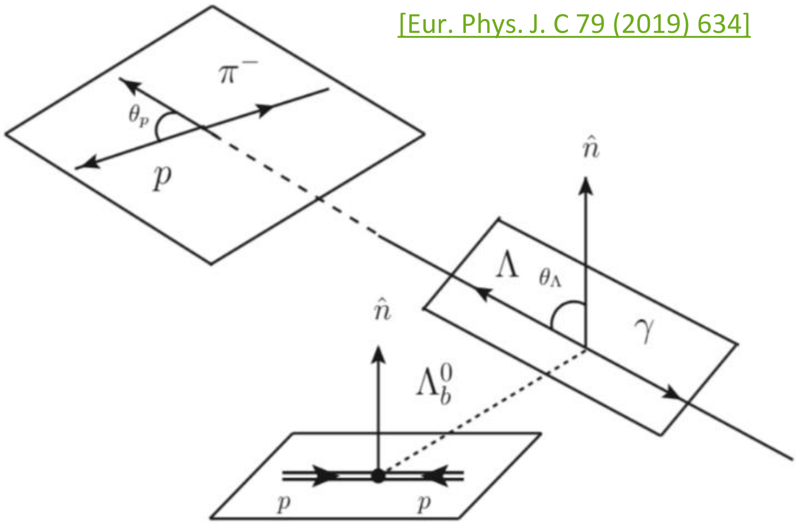
- $\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$

[Phys. Rev. Lett. 123, 031801]

$$\Lambda_b \to \Lambda\,\gamma$$
$$\Lambda \to p\,\pi$$

First angular analysis of radiative *b*-baryon decays using 6 fb^{-1} collected by LHCb Run 2.

[Eur. Phys. J. C 79 (2019) 634]



Radiative *b*-baryon decays reconstruction is challenging at LHCb.

- No photon direction and neutral long-lived particle → No secondary vertex.

Photon polarization in $\Lambda_b \to \Lambda\gamma$ decays

NEW

LHCb-PAPER-2021-030 (in preparation)

Direct access to the photon polarization (α_γ) due to the rich angular structure of the b-baryon decay.

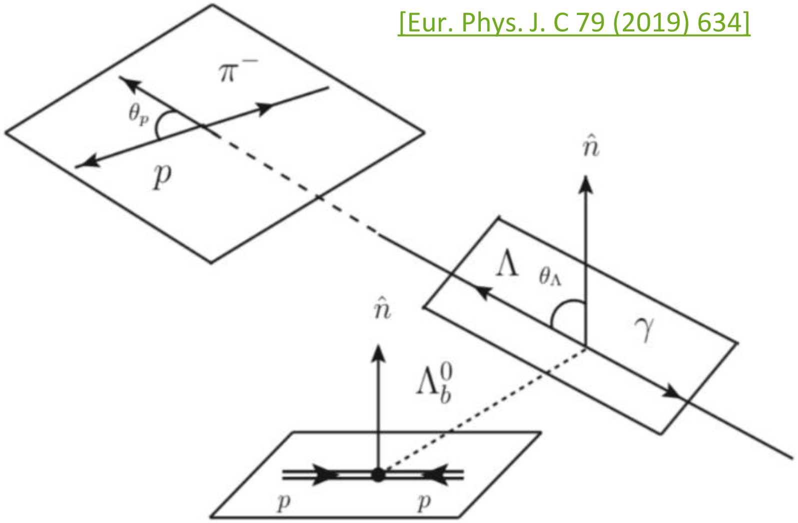
- Non-zero spin of initial and final particles.

$$\alpha_\gamma = \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R} = \frac{1-|r|^2}{1+|r|^2} \sim \mathbf{1}\ (\text{S.M.})$$

Angular structure

[Eur. Phys. J. C 79 (2019) 634]

$$dW(\theta_p, \theta_\Lambda) \propto 1 - \alpha_\Lambda P_{\Lambda_b} \cos\theta_p \cos\theta_\Lambda - \alpha_\gamma \left(\alpha_\Lambda \cos\theta_p - P_{\Lambda_b} \cos\theta_\Lambda\right)$$



Integrating over θ_Λ:

$$dW(\theta_p) \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p$$

Access to α_γ up to α_Λ.

Photon polarization in $\Lambda_b \to \Lambda\gamma$ decays

NEW

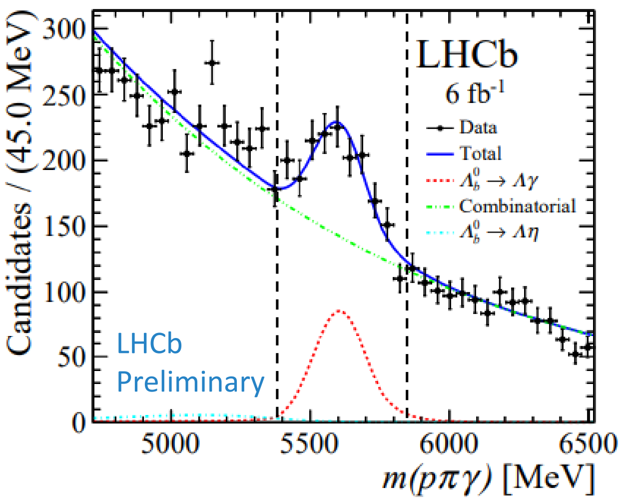
LHCb-PAPER-2021-030 (in preparation)

Strategy

Mass fit to $m(p\pi\gamma)$

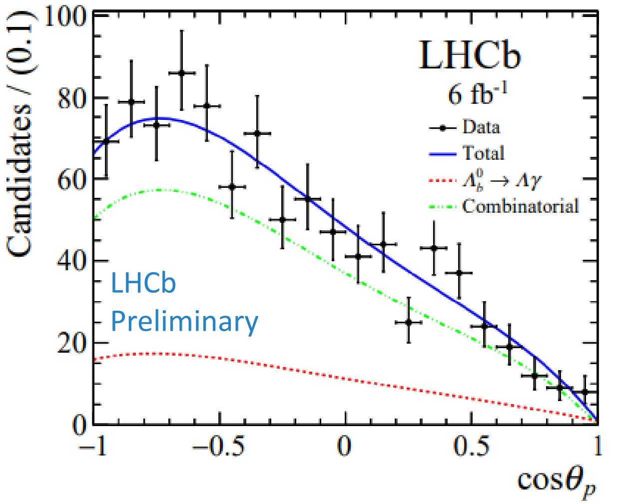
- Three components: signal, combinatorial background and partially reconstructed background.
- Yield in the signal region.

$$N_{\Lambda_b \to \Lambda\gamma} = 440 \pm 40$$



Angular fit to $\cos\theta_p$ in the signal region

- Angular acceptance for signal mode from simulation.
  - $\Lambda_b \to \Lambda\, J/\psi$ control data-simulation agreement.
- Background shape from $m(p\pi\gamma)$ side-bands



Photon polarization in $\Lambda_b \to \Lambda\gamma$ decays

NEW

LHCb-PAPER-2021-030 (in preparation)

Results

$$\alpha_\gamma^{Fit} = 0.82 \pm 0.23\ (\text{stat.})$$

Photon polarization is physically bounded:

$$\alpha_\gamma = \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R} \in [-1, 1]$$

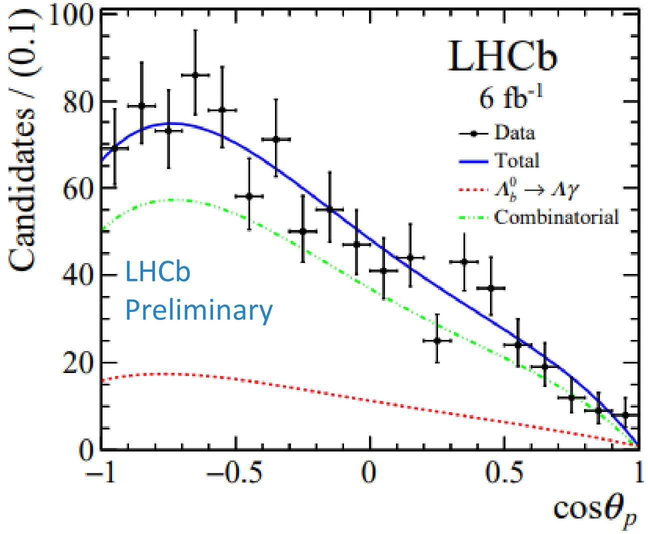
Feldman Cousins technique to determine confidence intervals within physical limits.

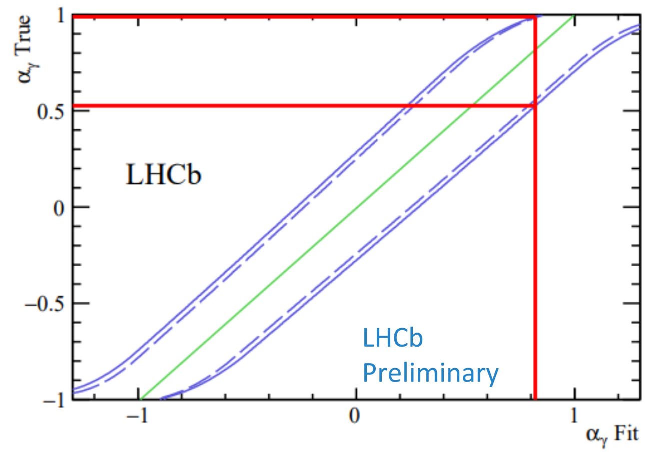
$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\ (\text{stat.})\ ^{+0.04}_{-0.13}\ (\text{syst.})$$

Uncertainties:

- Analysis statistically limited.
- Main systematics from background modeling.

Improvement with more luminosity (Run 3).





Photon polarization in $\Lambda_b \to \Lambda\gamma$ decays

NEW

LHCb-PAPER-2021-030 (in preparation)

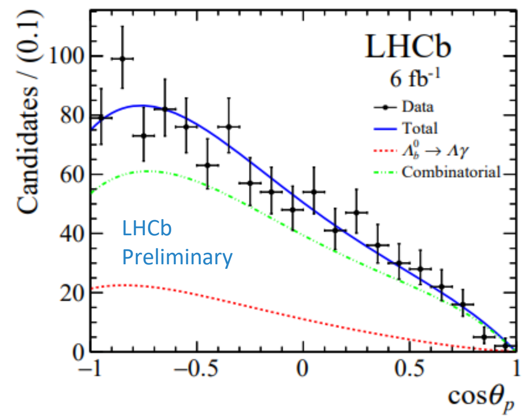
Results

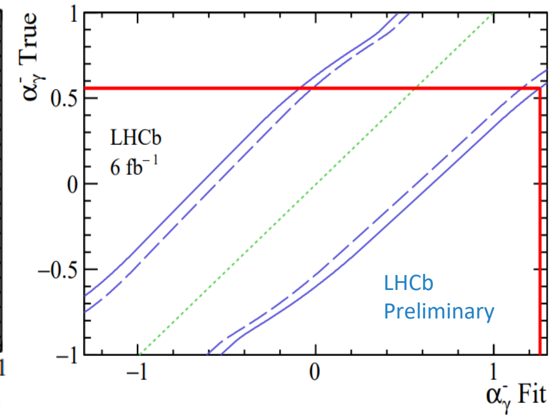
CP-test on $\Lambda_b \to \Lambda\gamma$ and $\overline{\Lambda}_b \to \overline{\Lambda}\gamma$ decays

$\Lambda_b \to \Lambda\gamma$

Fit: $\alpha^-_{\gamma,} = 1.26 \pm 0.42$

$\alpha^-_\gamma > 0.56\ (0.44)$ at 90% (95%)

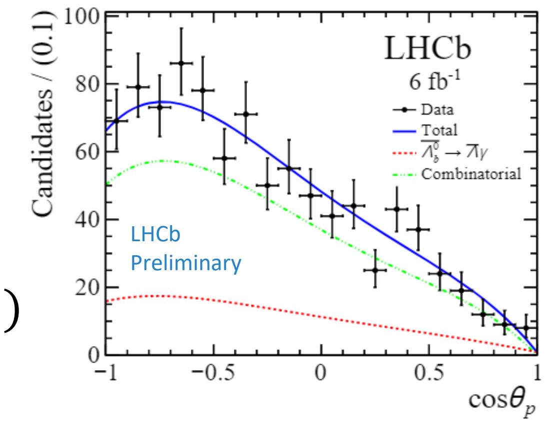


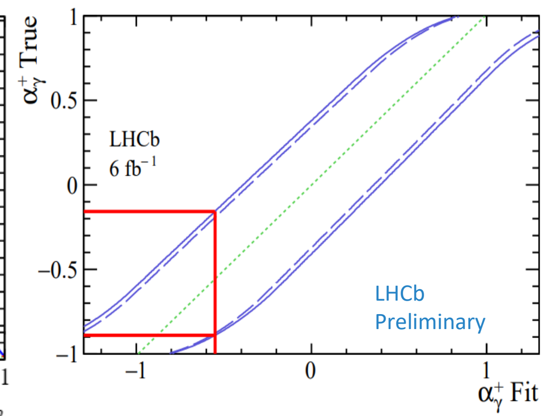


$\overline{\Lambda}_b \to \overline{\Lambda}\gamma$

Fit: $\alpha^+_{\gamma,} = -0.55 \pm 0.32$

$$\alpha^+_\gamma = -0.56^{+0.36}_{-0.33}\,(stat.)\,^{+0.16}_{-0.09}\,(syst.)$$





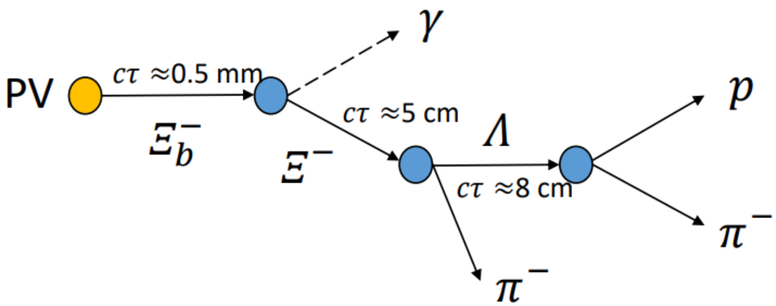
Search for $\Xi_b^- \to \Xi^- \gamma$ NEW

LHCb-PAPER-2021-017 (in preparation)

First search for $\Xi_b^- \to \Xi^- \gamma$ decay mode.

- $\mathcal{B}(\Xi_b^- \to \Xi^- \gamma)_{\text{theo}} = (1.23 \pm 0.64) \times 10^{-5}$

[arXiv:2008.06624]



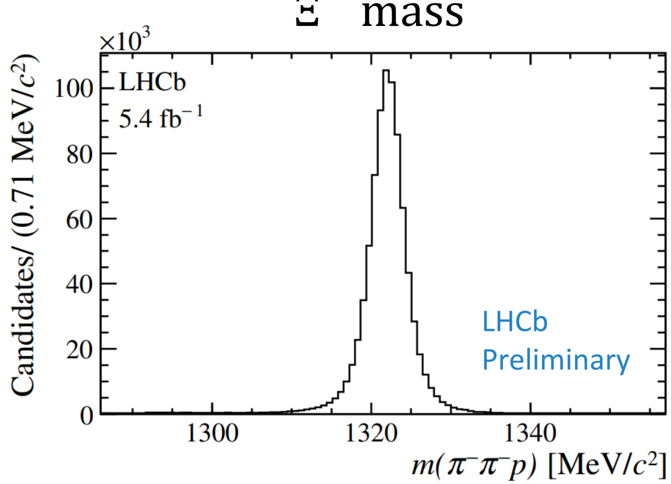
Analysis uses 5.4 fb^{-1} LHCb Run 2 data.

Strategy

Three displaced vertices

- Only decays inside the LHCb vertex (VELO) locator are considered.
- Requirements on Ξ^-, Λ masses.

Ξ^- mass



Multivariate classifier to discriminate signal from background.

Control channel: $\Xi_b^- \to \Xi^- J/\psi$

Search for $\Xi_b^- \to \Xi^- \gamma$ NEW

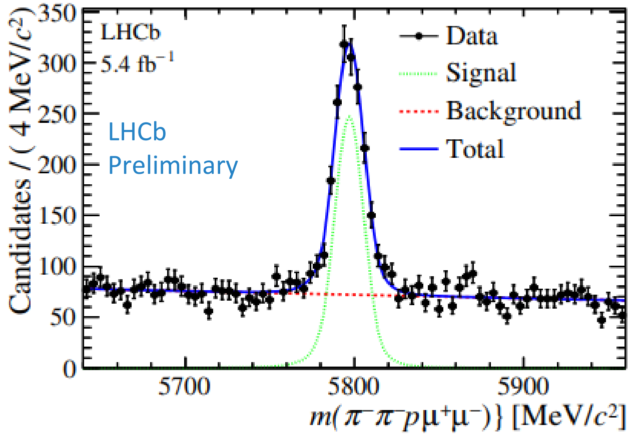
LHCb-PAPER-2021-017 (in preparation)

Signal yield

Simultaneous mass fit to $\Xi_b^- \to \Xi^- \gamma$ and $\Xi_b^- \to \Xi^- J/\psi$.

Signal and combinatorial background components.

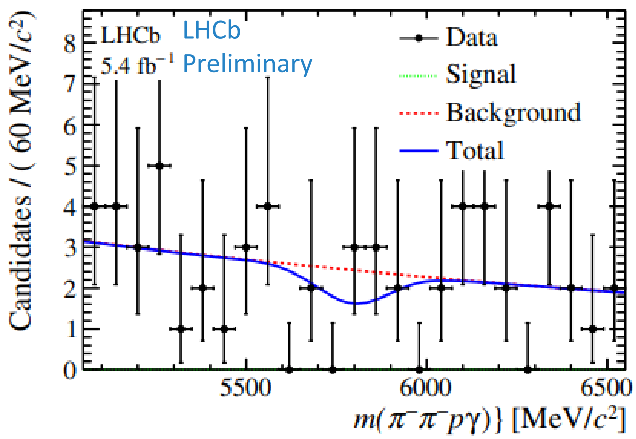
$$N(\Xi_b^- \to \Xi^- \gamma) = -3.6 \pm 3.9$$
$$N(\Xi_b^- \to \Xi^- J/\psi) = 1407 \pm 52$$



Branching ratio

$$\mathcal{B}(\Xi_b^- \to \Xi^-\gamma) = \mathcal{B}(\Xi_b^- \to \Xi^- J/\psi)\mathcal{B}(J/\psi \to \mu^+\mu^-) \times \frac{\epsilon(\Xi_b^- \to \Xi^- J/\psi)}{\epsilon(\Xi_b^- \to \Xi^-\gamma)} \frac{N(\Xi_b^- \to \Xi^-\gamma)}{N(\Xi_b^- \to \Xi^- J/\psi)}$$

$\mathcal{B}(\Xi_b^- \to \Xi^- J/\psi)$ (Dominates syst. uncertainty)



Search for $\Xi_b^- \to \Xi^- \gamma$ NEW

LHCb-PAPER-2021-017 (in preparation)

Results

First limit of $\Xi_b^- \to \Xi^- \gamma$

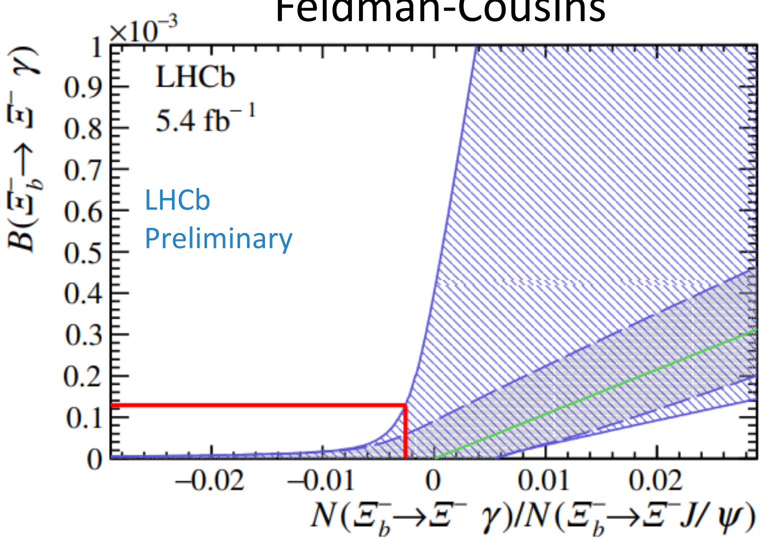
$$\mathcal{B}(\Xi_b^- \to \Xi^-\gamma) < 1.3\,(0.6) \times 10^{-4} \text{ at } 95\%\,(90\%)\text{ CL}.$$

Main source of systematic uncertainty from $\Xi_b^- \to \Xi^-$ J/ψ BR.

$$\frac{\mathcal{B}(\Xi_b^- \to \Xi^-\gamma)}{\mathcal{B}(\Xi_b^- \to \Xi^- J/\psi)} < 0.12\,(0.08) \text{ at } 95\%\,(90\%)\text{ CL}$$

LHCb Run 3 improvements on trigger and increase in luminosity, critical to achieve an observation.

Feldman-Cousins



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

$B^0 \to K^* e^+ e^-$ at very low q^2 [JHEP 2012 (2020) 081]

Run 1+2 ($9\mathrm{fb}^{-1}$) analysis.

Decay is dominated by $b \to s\gamma$ pole at very low $q^2 \in [0.0008 - 0.257]\ \mathrm{GeV}^2$.

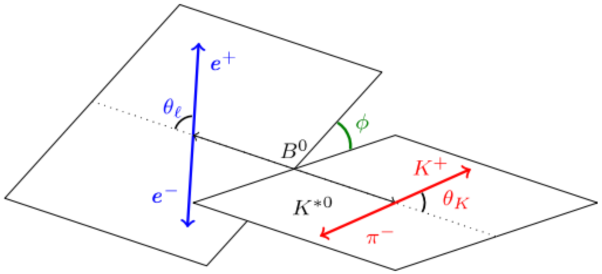
Three relevant angles:

- $\theta_l, \theta_K, \tilde{\phi}$

Four angular observables:

- $F_L, A_T^{Re}, A_T^{(2)}, A_T^{Im}$

Sensitive to the polarization of the virtual photon.



$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} =$$
$$= \frac{9}{16\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + (1-F_L)A_T^{Re}\sin^2\theta_K\cos\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi} + \frac{1}{2}(1-F_L)A_T^{Im}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Big]$$

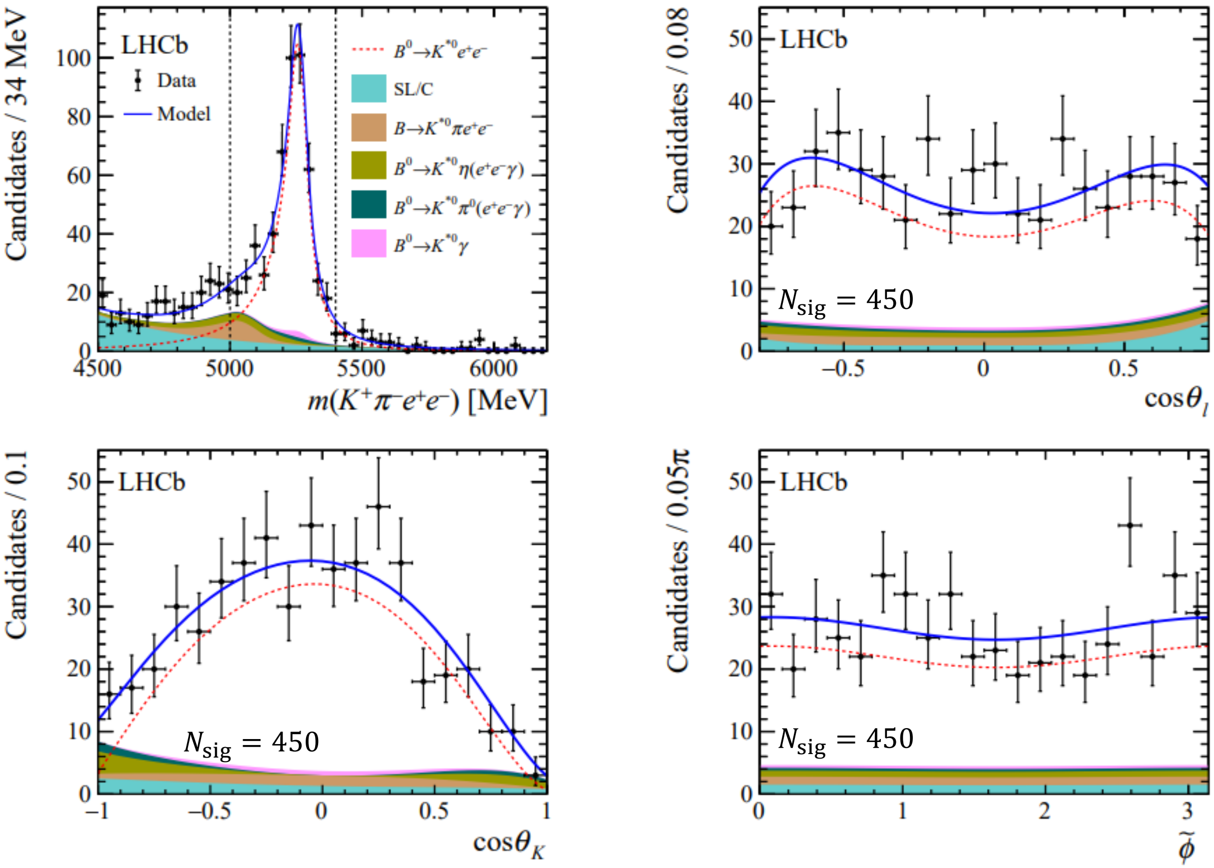
$$A_{R(L)} \equiv A_{R(L)} e^{i\phi_{R(L)}},\quad \tan\chi \equiv |C_7'/C_7|$$
$$A_T^{(2)} \simeq \sin(2\chi)\cos(\phi_L - \phi_R),$$
$$A_T^{Im} \simeq \sin(2\chi)\sin(\phi_L - \phi_R),$$

[Nucl. Phys. B854 (2012) 321]

$B^0 \to K^* e^+ e^-$ results

[JHEP 2012 (2020) 081]

Simultaneous fit: $m(K^+\pi^-e^+e^-), \cos\theta_l, \cos\theta_K, \tilde{\phi}$

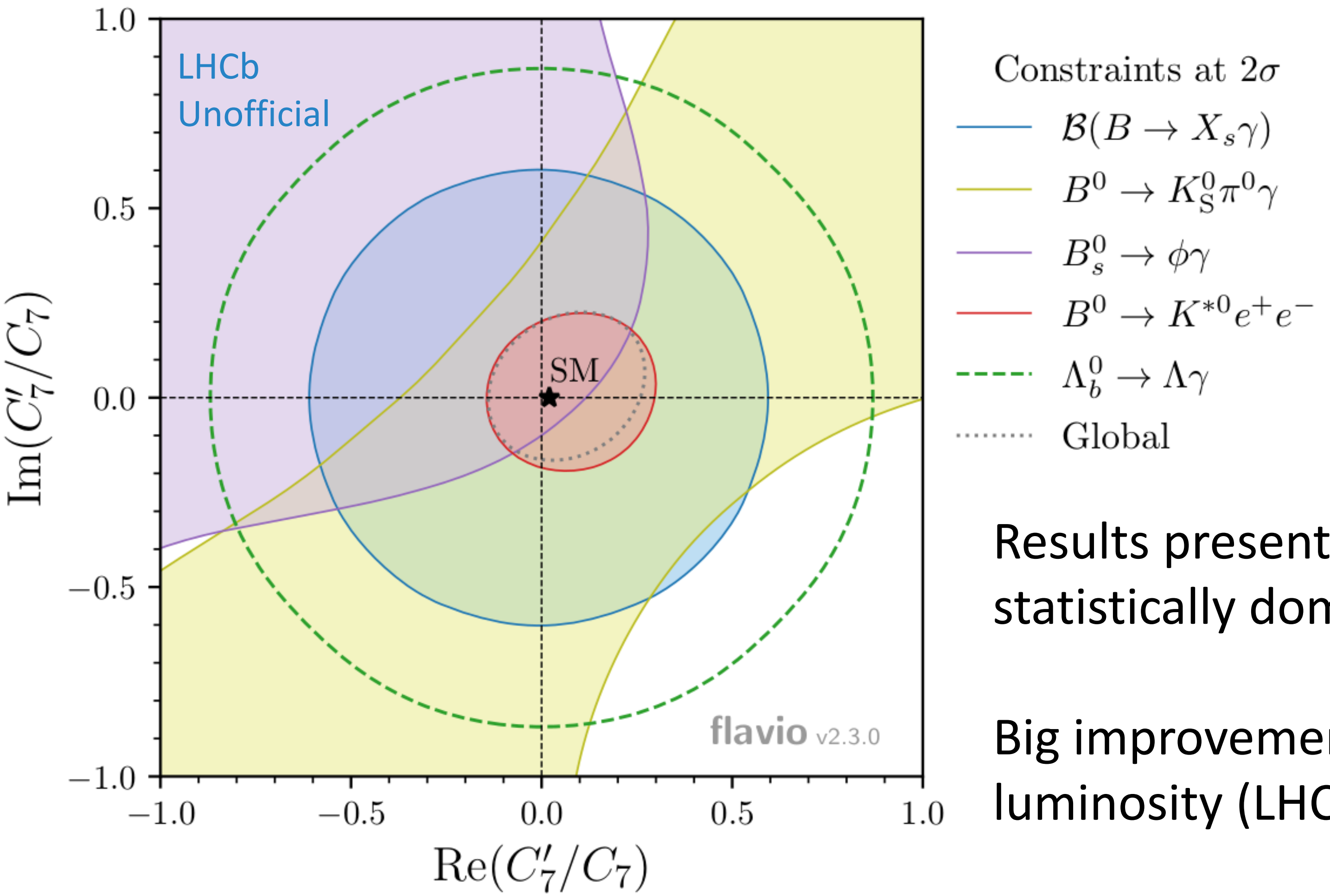


$$F_L = 0.044 \pm 0.026 \pm 0.014,$$
$$A_T^{Re} = -0.06 \pm 0.08 \pm 0.02,$$
$$A_T^{(2)} = +0.11 \pm 0.10 \pm 0.02,$$
$$A_T^{Im} = +0.02 \pm 0.10 \pm 0.01,$$

Uncertainty statistically dominated.

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

Results



Results presented are statistically dominated.

Big improvements with more luminosity (LHCb Run 3).

Summary

- The radiative transition $b \to s(d)\,\gamma$ is sensitive to New Physics and LHCb has access to it.
    - Different decay modes and observables.
    - Strongest constrains to C_7 and C_7'.
    - Unique access to radiative *b*-baryons decays.

- New LHCb results:
    - Photon polarization measurement in $\Lambda_\mathrm{b} \to \Lambda\gamma$ decays.
    - First limit on BR of $\Xi_b^- \to \Xi^-\,\gamma$.
    - Angular analysis $B^0 \to K^* e^+ e^-$ at very low q^2.

- Expect more precise results from Run 2 data and the upcoming LHCb Run 3.

BACK-UP

Photon polarization in $\Lambda_b \to \Lambda\gamma$ decays

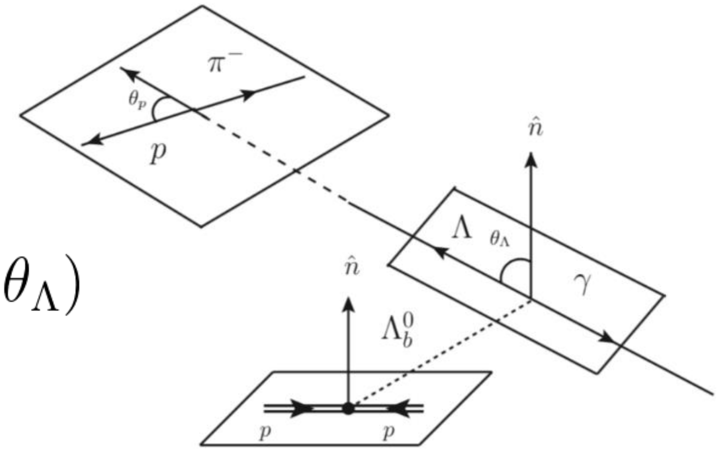
Angular structure

$$dW(\theta_p) \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p$$

$\alpha_\Lambda = 0.754 \pm 0.04$ [BESIII]

$$\alpha_\Lambda^- = 0.750 \pm 0.009 \pm 0.004$$
$$\alpha_\Lambda^+ = -0.758 \pm 0.010 \pm 0.007$$

$$dW(\theta_p, \theta_\Lambda) \propto 1 - \alpha_\Lambda P_{\Lambda_b} \cos\theta_p \cos\theta_\Lambda - \alpha_\gamma \left(\alpha_\Lambda \cos\theta_p - P_{\Lambda_b} \cos\theta_\Lambda\right)$$



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

Normalization channel

$$\Gamma(\Xi_b^- \to \Xi^- J/\psi) = \left(\frac{3}{2} \pm 0.45\right) \cdot \Gamma(\Lambda_b \to \Lambda J/\psi)$$

SU(3)

[arXiv:1510.05568]

Parameter	Value
τ_{Ξ_b}	1.57 ± 0.04 ps [23]
$\tau_{\Lambda_b^0}$	1.47 ± 0.01 ps [23]
$\mathcal{B}(\Lambda_b^0 \to \Lambda J/\psi)$	$(3.36 \pm 1.11) \times 10^{-4}$ [33, 34]

[23] (PDG)

[33]

[34] (HFLAV)

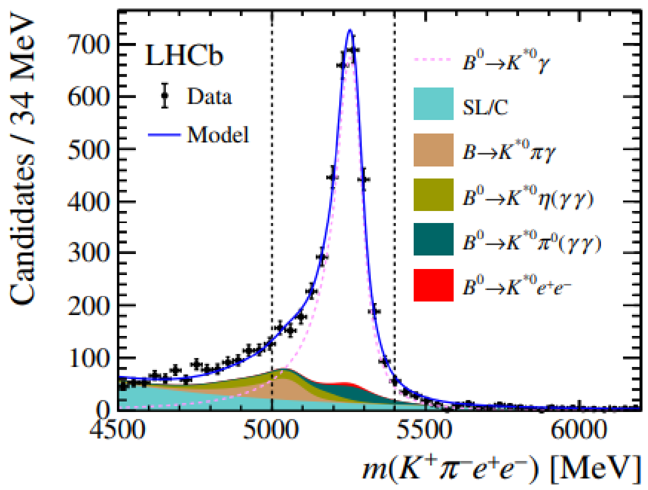
$$\mathcal{B}(\Xi_b^- \to \Xi^- J/\psi) = \left(\frac{3}{2} \pm 0.45\right) \frac{\tau_{\Xi_b}}{\tau_{\Lambda_b^0}} \mathcal{B}(\Lambda_b^0 \to \Lambda J/\psi) = (5.4 \pm 2.4) \times 10^{-4}$$

$B^0 \to K^* e^+ e^-$ strategy

[JHEP 2012 (2020) 081]

Control channel: $B^0 \to K^*(\gamma \to e^+e^-)$

- Same final state.
- Larger branching ratio.
- Fit F_L from $\cos\theta_K$ as validation.



Simultaneous fit:

- $m(K^+\pi^-e^+e^-), \cos\theta_l, \cos\theta_K, \tilde{\phi}$
- Reduced mass region.
- Background modeling mainly from simulation and data.