Radiative decays at LHCb

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EPP Warwick Seminar
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1 Introduction
   - Theoretical motivation
   - LHCb Detector
   - Experimental challenges

2 Analyses
   - $B_s \to \phi \gamma$ time-dependent analysis
   - $B \to K^* ee$ angular analysis
   - $\Lambda^0_b \to \Lambda \gamma$ (angular) analysis
   - Ongoing analyses

3 Conclusions and prospects
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3 Conclusions and prospects
The $b \rightarrow s\gamma$ 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

\[
\mathcal{H}_{\text{eff}} = -4 \frac{G_F}{\sqrt{2}} V^*_{ts} V_{tb} \left( C_7 O_7 + C'_7 O'_7 \right)
\]
The $b \rightarrow s\gamma$ 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

$$H_{\text{eff}} = -4 \frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} (C_7 O_7 + C'_7 O'_7)$$

Wilson coefficient can be constrained through measurement of:

- Branching ratio: $B_{\text{rad}} \propto |C_7|^2 + |C'_7|^2$
- Photon polarization: $\alpha_{\gamma}^{LO} = \frac{1 - |C'_7|^2}{1 + |C'_7|^2}$
- CP asymmetry: $A_{\text{CP}} \propto \text{Im} \frac{C_7 C'_7}{|C_7|^2 + |C'_7|^2}$
Photons in such transitions are mainly **left-handed in the SM** since the $W$ boson couples to left-handed quarks.

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

Wilson coefficient can be constrained through measurement of:

- **Branching ratio**: $B_{\text{rad}} \propto |C_7|^2 + |C_7'|^2 \sim 0$

- **Photon polarization**: $\alpha_{\gamma}^{LO} = \frac{1 - |C_7'|^2}{1 + |C_7'|^2} \sim 0$

- **CP asymmetry**: $A_{CP} \propto \text{Im} \frac{C_7 C_7'}{|C_7|^2 + |C_7'|^2} \sim 0$
LHCb detector

- One of the four detector at LHC
- LHCb is a single-arm \((2 < \eta < 5)\) spectrometer
  - Optimised for beauty and charm decays
- Runs at lower luminosity
  - Optimised for precision measurements

\[ \eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right) \]

\(\eta\): Angle between \(p\) and positive beam axis.
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$\Delta IP = \left(16 + \frac{29}{p_T} \text{ [GeV]} \right) \, \mu m$
LHCb detector

Great Secondary Vertex (SV) and Impact Parameter (IP) resolution

Very good $p$, $p_T$ and mass resolution

$\Delta p/p = 0.5 - 1.0\%$
LHCb detector

Great Secondary Vertex (SV) and Impact Parameter (IP) resolution

Particle ID mostly done by two RICH detectors, complemented by other subdetectors

Very good $p, p_T$ and mass resolution

Kaon ID $\sim 95\%$ for $\sim 5\% \pi \to K$ mis-id probability

[JINST3 (2008) S08005]
Electron ID $\sim 90\%$ for $\sim 5\%$ $e \rightarrow h$ mis-id probability

$$\Delta E/E_{\text{ECAL}} = 1\% + 10.0\%/\sqrt{E[\text{GeV}]}$$
Muon ID $\sim 97\%$ for $\sim 1-3\% \pi \rightarrow \mu$ mis-id probability
LHCb detector

Long tracks
- Hits at least in VELO and T stations
- Used in majority of analyses

Downstream tracks
- Hits in TT and T stations (not in VELO)
- Decay products of long-lived particles
Challenges for analysis involving neutrals ($\gamma$ and $\pi^0$):

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

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- Decays involving long-lived particles ($K_S$, $\Lambda^0$, $\Xi^-$)
  - Decay after the VELO
    - Worse IP/vertex position resolution
    - Hlt1 (trigger) only selects Long tracks
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3 Conclusions and prospects
Time-dependent analysis of $B_s \to \phi\gamma$ decay

Time-dependent decay rates of $B_s \to \phi\gamma$ and $\bar{B}_s \to \phi\gamma$ grant access to photon polarization:

$$\Gamma_{B_s \to \phi\gamma}(t) \propto e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - A^\Delta_{\phi\gamma} \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) + C_{\phi\gamma} \cos (\Delta m_s t) - S_{\phi\gamma} \sin (\Delta m_s t) \right]$$

$$\Gamma_{\bar{B}_s \to \phi\gamma}(t) \propto e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - A^\Delta_{\phi\gamma} \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) - C_{\phi\gamma} \cos (\Delta m_s t) + S_{\phi\gamma} \sin (\Delta m_s t) \right]$$

- $A^\Delta_{\phi\gamma}$ and $S_{\phi\gamma}$ are sensitive to photon polarization
- $C_{\phi\gamma}$ is related to direct CP violation
- SM prediction close to zero for $A^\Delta_{\phi\gamma}$, $C_{\phi\gamma}$ and $S_{\phi\gamma}$
- $A^\Delta$ only accessible for $B_s$ decays:
  - $\Delta \Gamma_s \sim 0.081 \pm 0.011$
  - $\Delta \Gamma_d \sim 0$
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- $A^\Delta$ only accessible for $B_s$ decays
- Previous: $A^\Delta_{\phi\gamma}$ measured in untagged analysis with Run I data at LHCb [LHCb: PRL118(2017)021801]

*Untag: No separation between $B_s$ and $\bar{B}_s$
Time-dependent analysis of $B_s \rightarrow \phi \gamma$ decay

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- $A^{\Delta}$ only accessible for $B_s$ decays
- Previous: $A_{\phi \gamma}^{\Delta}$ measured in untagged* analysis with Run I data at LHCb [LHCb: PRL118(2017)021801]

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Time-dependent decay rates of $B_s \rightarrow \phi \gamma$ and $\overline{B_s} \rightarrow \phi \gamma$ grant access to photon polarization:

\[
\Gamma_{B_s \rightarrow \phi \gamma}(t) \propto e^{-\Gamma_{s}t} \left[ \cosh \left(\frac{\Delta \Gamma_{s}t}{2}\right) - A_{\phi \gamma}^\Delta \sinh \left(\frac{\Delta \Gamma_{s}t}{2}\right) + C_{\phi \gamma} \cos (\Delta m_s t) - S_{\phi \gamma} \sin (\Delta m_s t) \right]
\]

\[
\Gamma_{\overline{B_s} \rightarrow \phi \gamma}(t) \propto e^{-\Gamma_{s}t} \left[ \cosh \left(\frac{\Delta \Gamma_{s}t}{2}\right) - A_{\phi \gamma}^\Delta \sinh \left(\frac{\Delta \Gamma_{s}t}{2}\right) - C_{\phi \gamma} \cos (\Delta m_s t) + S_{\phi \gamma} \sin (\Delta m_s t) \right]
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- Previous: $A^\Delta_{\phi \gamma}$ measured in untagged analysis with Run I data at LHCb [LHCb: PRL118(2017)021801]
- New: $S_{\phi \gamma}$ and $C_{\phi \gamma}$ measurement using tagging [PRL123(2019)081802]

*Tagging: Separation between $B_s$ and $\overline{B_s}$ [JINST11(2016)P05010]
Time-dependent analysis of $B_s \rightarrow \phi\gamma$

- Mass fit of $B_s \rightarrow \phi\gamma$ (signal) and $B \rightarrow K^*\gamma$ (control) decays
- Using Run 1 data at LHCb [PRL123(2019)081802]
- Background subtracted with sPlot technique, fitting the B mass

**Signal: $B_s \rightarrow \phi\gamma$**

- Data
- Model
- Signal
- Peaking
- Combinatorial

**Control: $B \rightarrow K^*\gamma$**

- Data
- Model
- Signal
- Peaking
- $B^0 \rightarrow K^{*0}\eta$
- Missing pion
- $B \rightarrow K\pi\pi^0X$
- Combinatorial

5300 signal yield

32000 signal yield
Time-dependent analysis of $B_s \rightarrow \phi \gamma$

- Mass fit of $B_s \rightarrow \phi \gamma$ (signal) and $B \rightarrow K^* \gamma$ (control) decays
- Using Run 1 data at LHCb [PRL123(2019)081802]
- Background subtracted with sPlot technique, fitting the B mass
- Decay time measured from B momentum and flight distance
- Need to control the proper time acceptance

![Graph showing decay time distribution with different acceptance regions]

$$A(t) = \frac{at^n}{1+at^n} \times (1+\beta t)$$
Time-dependent analysis of $B_s \rightarrow \phi \gamma$: Proper time fit

Analysis strategy:
- Simultaneous unbinned ML fit to $B_s \rightarrow \phi \gamma$ (signal) and $B \rightarrow K^* \gamma$ (control) channels
- Mis-tag probability and resolution evaluated per event

$S_{\phi \gamma} = 0.43 \pm 0.30 \pm 0.11,$
$C_{\phi \gamma} = 0.11 \pm 0.29 \pm 0.11,$
$A^\Delta_{\phi \gamma} = -0.67^{+0.37}_{-0.41} \pm 0.17$

- Compatible with SM at 1.3, 0.3, 1.7 $\sigma$
- First measurement of $S$ and $C$ in the $B_s \rightarrow \phi \gamma$ decay [PRL123(2019)081802]
$S_{CP}$ and $C_{CP}$ in $b \to s \gamma$ transitions

- Measurement competitive with other results from $b$-factories
$B \rightarrow K^* ee$ angular analysis

Decay dominated by $b \rightarrow s \gamma$ at very-low $q^2 = m_{ee}^2$ pole

- Virtual $\gamma$ decaying in an observable $\ell^+ \ell^-$ pair
- Previous analysis with Run 1 data [JHEP04(2015)064]
- Recent update including Run 1 + Run 2 data [JHEP12(2020)081]
- All final state particles are charged ($K^+ \pi^- e^+ e^-$)
$B \rightarrow K^* ee$ angular analysis

Electrons lose energy by radiation (bremsstrahlung)
- difficult to reconstruct
- need bremsstrahlung recovery

→ adding neutral clusters from the ECAL, with $E_T > 75$ MeV

Long radiative tail in the B mass distribution: controlled from $B \rightarrow K^* \gamma$ events ($\gamma \rightarrow e^-e^+$, with bremsstrahlung emission)
Angular distribution with three angles: $\cos \theta_K$, $\cos \theta_L$, $\phi$

Angular observables granting access to the photon polarization:

- $A^{(2)}_T (q^2 \rightarrow 0) = \frac{2 \text{Re}(C_7 C_7^*)}{|C_7|^2 + |C_7'|^2}$
- $A^{\text{Im}}_T (q^2 \rightarrow 0) = \frac{2 \text{Im}(C_7 C_7^*)}{|C_7|^2 + |C_7'|^2}$
$B \rightarrow K^* ee$ angular analysis

Fit to the B mass and angles (in reduced mass region)

[JHEP12(2020)081]
This analysis set strong constraints in the $C_7 - C'_7$ plane.
Still statistically limited

precision will improve with Upgrade

[JHEP12(2020)081]
Radiative $b$-baryon decays:

- Non-zero spin grants access to more observables
- Two spectator quarks $\Rightarrow$ different form factors
- Photon polarization has never been measured!!
- $b$-baryons only at accessible $pp$ colliders (LHC)
First observation: $\Lambda_b^0 \rightarrow \Lambda \gamma$

First observation of a radiative $b$-baryon decay using 2016 data ($\mathcal{L} = 1.67 \text{ fb}^{-1}$) [PRL123(2019)031801]:

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

- Observed with $5.6\sigma$ significance
- Open door to photon polarization measurement
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- Open door to photon polarization measurement
Angular distribution: $\Lambda_b \to \Lambda\gamma$

Angular distribution for $\Lambda_b$ decay:

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

Integrating in helicity angles:

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

$$\Gamma_{\Lambda_b}(\theta_p) = \frac{1}{4} \left( 1 - \alpha_\gamma \alpha_\Lambda \cos \theta_p \right)$$

The decay parameters are:

- $P_{\Lambda_b} = 0.00 \pm 0.06 (\text{stat}) \pm 0.06 (\text{sys})$ [PhysRevD.97(2018)072010]
- $\alpha_\Lambda = 0.732 \pm 0.010$ [PDG 2020]
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Integrating in helicity angles:

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

$$\Gamma_{\Lambda_b}(\theta_p) = \frac{1}{4} \left( 1 - \alpha_\gamma \alpha_\Lambda \cos \theta_p \right)$$

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Angular distribution for $\Lambda_b$ decay:

$$\Gamma_{\Lambda_b} = \frac{1}{4} \left( 1 - \alpha_\gamma \alpha_\Lambda \cos \theta_p \right)$$

The value of the $\Lambda$ decay parameter is:

$$\alpha_\Lambda = 0.732 \pm 0.010 \ [\text{PDG 2020}]$$
Statistical sensitivity to photon polarization

Sensitivity to the photon polarization ($\alpha_\gamma$) [EPJC(2019)79:634]:

- Measuring $P_{Hb}$ as well does not reduce the sensitivity to $\alpha_\gamma$
  - For a large data sample
- Similar $\alpha_\gamma$ sensitivity using $\Lambda_b$ and $\Xi_b^-$ systems
- Only considering the theoretical angular polarization:
  - $\sigma_\alpha \sim 0.25$ with $\Lambda^0_b \rightarrow \Lambda\gamma$ 2016 data sample (65 events)
  - $\sigma_\alpha \sim 0.15$ with $\Lambda^0_b \rightarrow \Lambda\gamma$ Run2 data sample (assuming 200 events)
Sensitivity studies

\[ \Gamma(\theta_\Lambda, \theta_p; \alpha_\gamma) = \left( \text{Signal}(\theta_\Lambda, \theta_p; \alpha_\gamma) \times A(\theta_\Lambda, \theta_p) \right) \ast \text{Res}(\theta_\Lambda, \theta_p) + \frac{S}{B}(BKG(\theta_\Lambda, \theta_p)) \]
Sensitivity studies

Independently testing the effects:

- **Statistical**: Shape of theoretical angular distribution
- **Resolution**: Effect of the detector
- **Acceptance**: Effect of the selection
- Studying the effect of the background:
  - with different angular background shapes
  - for several signal over background ratios

**Acceptance/Resolution**

\[
\Lambda_b \to \Lambda \gamma
\]

![Acceptance/Resolution graph](image)

**Background**

\[
\Lambda_b \to \Lambda \gamma
\]

![Background graph](image)

Tested for 1k events [EPJC(2019)79:634]

L.M. Garcia
Radiative decays at LHCB
Sensitivity studies

Independently testing the effects:
- **Statistical**: Shape of theoretical angular distribution
- **Resolution**: Effect of the detector (negligible effect)
- **Acceptance**: Effect of the selection (asymmetric with $\alpha_\gamma$)
- Studying the effect of the background:
  - with different angular background shapes
  - for several signal over background ratios

**Acceptance/Resolution**

```
\[ \Lambda_b \rightarrow \Lambda \gamma \]
```

**Background**

```
\[ \Lambda_b \rightarrow \Lambda \gamma \]
```

Tested for 1k events [EPJC(2019)79:634]
Fit strategy: $\Lambda_b \rightarrow \Lambda\gamma$

The photon polarization will be extracted using the PDF:

$$\Gamma(\theta_p; \alpha_\gamma) = \frac{S}{S + B} \left( \text{Signal}(\theta_p; \alpha_\gamma) \times A(\theta_p) \right) + \frac{B}{S + B} \left( \text{BKG}(\theta_p) \right)$$

- Using Run 2 data in $\Lambda_b^0$ mass$_{PDG} \pm 2.5\sigma$
- **Signal**: $\frac{1}{4} \left( 1 - \alpha_\gamma \alpha_\Lambda \cos \theta_p \right)$
- **Resolution**: Negligible effect
- **Acceptance**: Extracted from MC, controlled from data ($\Lambda_b \rightarrow \Lambda J/\psi$)
- **Background**: Extracted from data mass side-bands
- **Signal fraction** is Gaussian constrained
- Sensitivity to $\alpha_\gamma$ studied in [EPJC(2019)79:634]
- **Expected** $\sigma_\gamma(\text{stat.}) \sim 0.32$ (WIP)
Λ_b^0 \rightarrow \Lambda \gamma \text{ analysis with Run 2 data}

(Blinded) Λ_b^0 \rightarrow Λ\gamma \text{ mass} 

(Toy) Λ_b^0 \rightarrow Λ\gamma \text{ ang dist} 

- Reconstruction and selection strategy defined using Run 2
- Background sources (other than combinatorial) found negligible
- Angular fit procedure established
  - Fitting signal and background, and including acceptance effects
- Systematics evaluated and found to be below 0.15
- Results (still blinded) will be delivered very soon!
$B \rightarrow K^+\pi^+\pi^-\gamma$ amplitude analysis

- First analysis observing a non-zero photon polarization at LHCb [PRL112(2014)161801]
- Interference with reasonance grant access to the photon polarization [EPJC79(2019)622]
- Using amplitude analysis to provide a direct measurement
- Expecting an statistical uncertainty of 0.014 [EPJC79(2019)622]
Search for $\Xi^-_b \rightarrow \Xi^- \gamma$

First search of the $\Xi^-_b \rightarrow \Xi^- \gamma$ decay

- No previous limit:
  - $\mathcal{B}(\Xi^-_b \rightarrow \Xi^- \gamma)_{\text{theo}} = (3.03 \pm 0.10) \times 10^{-4}$ [PRD83(11)054007]
  - $\mathcal{B}(\Xi^-_b \rightarrow \Xi^- \gamma)_{\text{theo}} = (1.23 \pm 0.64) \times 10^{-5}$ [arXiv:2008.06624]

- Only 5% events accessible (HLT1)
- Use of $\Xi^-_b \rightarrow \Xi^- J/\psi$ for normalization removes dependence with $f_{\Xi^-_b}$
- Still blinded
- Expected to set an upper limit of $\mathcal{O}(10^{-4})$

![Graph showing the search results for $\Xi^-_b \rightarrow \Xi^- \gamma$](image)
\[ \Lambda^0_b \rightarrow (\Lambda^* \rightarrow pK^-) \gamma \] amplitude analysis

- **Goal:** Gain knowledge on the \( pK \) spectrum
  - Aid in the interpretation of the LFU measurement \( (R_{pK}) \)
  - Pentaquarks: Set an upper limit on \( \mathcal{B}(P_c \rightarrow p\gamma) \)
    - \( P_c \rightarrow pJ/\psi \) was observed in \( \Lambda^0_b \rightarrow pK^- J/\psi \) [PRL115(2015)072001]

- 2D fit in \( m_{pK} \) and \( m_{p\gamma} \)
- Isobar model with parameters from PDG when available

![Graphs showing 2D fits in \( m_{pK} \) and \( m_{p\gamma} \) with pull distributions.](image-url)
Other radiative decays

Search for $\Lambda_b \rightarrow p\pi\gamma$
- $b \rightarrow d\gamma$ transition:
  - More suppressed
  - Larger CPV
- No previous limit
- $pK\gamma$ and $K\pi\gamma$ contaminations controlled by simultaneous fit

Radiative charm decays:
$D \rightarrow K^*\gamma, \phi\gamma, \rho\gamma$
- $c \rightarrow u\gamma$ transition
- $\mathcal{B} \sim 10^{-4} - 10^{-5}$
- Cleaner NP probes ($A_{CP}, \gamma$ pol.) [JHEP08(2017)091]
- More background
  - Softer $\gamma$
  - $\mathcal{B}(D \rightarrow V^0\pi^0) \gg \mathcal{B}(V^0\gamma)$
Non-hadronic radiative decays

Search for $B_s \rightarrow \mu \mu \gamma$ with Run 2 data

- Sensitive to $C_7$, $C_9$ and $C_{10}$
- $\mathcal{B}_{SM} \sim 10^{-9} - 10^{-10}$
- BaBar limit $\mathcal{B} < 10^{-7}$

Search for $\gamma \gamma$ final states ($B_s$ and ALPs)

- Light ALPs not reachable for ATLAS/CMS
- $\mathcal{B}_{SM} \sim 10^{-7}$
- Belle limit $\mathcal{B} < 3 \times 10^{-6}$
- Challenging topology
Introduction
- Theoretical motivation
- LHCb Detector
- Experimental challenges

Analyses
- $B_s \rightarrow \phi \gamma$ time-dependent analysis
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Conclusions and prospects
Prospects: Converted photons

When photons convert before the magnet ($\gamma \rightarrow e^+ e^-$):
- $e^+ e^-$ tracks can be reconstructed $\implies$ resolution 3 times better
- Allow to access $|V_{td}/V_{ts}|$ suppressed modes like $B_s \rightarrow K^*\gamma$
- Its rate is 20 times lower than for calo photons

For Run 3:
- Converted photon analyses feasible with more luminosity
- Improvements in electron tracking for Upgrade
Conclusions

- The **photon polarization** is being measured at LHCb using several channels and different observables.
- Important constraints to the Wilson coefficient $C_7^{(')}$.
- Nice competition ahead with Belle II.

**Preparations for Run 3:**
- Developing fast downstream tracking algorithms fitting Hlt1 time-budget.
  - Can increase statistics in b-baryon analysis up to 20 times.
- Including BDT methods to Hlt2 lines:
  - Better sgl/bkg separation.
  - Add downstream to channels with huge bkg.
Thanks for your attention
The branching ratio can be extracted from the signal yield:

\[ N = 2 \times \mathcal{L} \times \sigma_{bb} \times f_{\Xi_b} \times B_{\Xi_b^{-} \rightarrow \Xi^{-} \gamma} \times B_{\text{sub-decays}} \times \epsilon_{sel} \]

The \( B \) is extracted as a ratio of \( B \) using dimuonic channels

- Same hadronic decay chain

\[
\frac{N(\Xi^{-}_b \rightarrow \Xi^{-} \gamma)}{N(\Xi^{-}_b \rightarrow \Xi^{-} J/\psi)} = \frac{B(\Xi^{-}_b \rightarrow \Xi^{-} \gamma)}{B(\Xi^{-}_b \rightarrow \Xi^{-} J/\psi)} \times \frac{1}{B(J/\psi \rightarrow \mu^+ \mu^-)} \times \frac{\epsilon_{sel}(\Xi^{-}_b \rightarrow \Xi^{-} \gamma)}{\epsilon_{sel}(\Xi^{-}_b \rightarrow \Xi^{-} J/\psi)}
\]

where:

- \( \epsilon_{sel} = \epsilon_{acc} \times \epsilon_{reco + strip} \times \epsilon_{trigger} \times \epsilon_{Presel} \times \epsilon_{PID} \times \epsilon_{BDT} \times \epsilon_{IsPhoton} \)
Why $\Xi^-_b \rightarrow \Xi^- J/\psi$ as normalization channel

\[
\mathcal{B}(\Xi^-_b \rightarrow \Xi^- J/\psi) = (5.0 \pm 2.4) \times 10^{-4}
\]
\[
\mathcal{B}(\Lambda^0_b \rightarrow \Lambda J/\psi) = (3.29 \pm 1.11) \times 10^{-4}
\]
\[
\mathcal{B}(\Lambda^0_b \rightarrow pK^- J/\psi) = (3.2 \pm 0.6) \times 10^{-4}
\]
\[
\frac{f_{\Xi^-_b}}{f_{\Lambda^0_b}} = (8.2 \pm 2.6) \times 10^{-4}
\]

\[
\mathcal{B}(\Xi^-_b \rightarrow \Xi^- \gamma) \propto \mathcal{B}(\Xi^-_b \rightarrow \Xi^- J/\psi) \quad \Rightarrow \quad \sigma = 48\%
\]
\[
\mathcal{B}(\Xi^-_b \rightarrow \Xi^- \gamma) \propto \frac{1}{f_{\Xi^-_b}/f_{\Lambda^0_b}} \mathcal{B}(\Lambda^0_b \rightarrow \Lambda \gamma) \quad \Rightarrow \quad \sigma = 46\%
\]
\[
\mathcal{B}(\Xi^-_b \rightarrow \Xi^- \gamma) \propto \frac{1}{f_{\Xi^-_b}/f_{\Lambda^0_b}} \mathcal{B}(\Lambda^0_b \rightarrow pK^- J/\psi) \quad \Rightarrow \quad \sigma = 37\%
\]

- When $\mathcal{B}(\Lambda^0_b \rightarrow \Lambda J/\psi)$ is measured by LHCb, $\sigma = 37\%$
- When $\mathcal{B}(\Xi^-_b \rightarrow \Xi^- J/\psi)$ is measured by LHCb, no $f_{H_b}$ dependency and $\sigma = 20\%$
Expected yields: $\Xi^{-}\rightarrow\Xi^{-}\gamma$

$$N = 2 \times \mathcal{L} \times \sigma_{b\bar{b}} \times f_{\Xi^{-}} \times B_{\Xi^{-}\rightarrow\Xi^{-}\gamma} \times B_{\text{sub-decays}} \times \epsilon_{\text{sel}}$$

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int \mathcal{L} \ [fb^{-1}]$</td>
<td>2.19</td>
</tr>
<tr>
<td>$\sigma_{b\bar{b}} \ [\mu b]$</td>
<td>$\sim 600$</td>
</tr>
<tr>
<td>$f_{\Xi^{-}} \ [%]$</td>
<td>0.021 $\pm$ 0.007</td>
</tr>
<tr>
<td>$B(\Xi^{-}\rightarrow\Xi^{-}\gamma)$</td>
<td>$(1.1 \pm 0.3) \times 10^{-5}$</td>
</tr>
<tr>
<td>$B(\Xi^{-}\rightarrow\Lambda^{0}\pi^{-}) \ [%]$</td>
<td>99.887 $\pm$ 0.035</td>
</tr>
<tr>
<td>$B(\Lambda^{0}\rightarrow p\pi) \ [%]$</td>
<td>63.9 $\pm$ 0.5</td>
</tr>
<tr>
<td>$\epsilon_{\text{sel}}$</td>
<td>$(4.3 \pm 0.2) \times 10^{-6}$</td>
</tr>
<tr>
<td>Expected yield</td>
<td>0.8 $\pm$ 0.4</td>
</tr>
</tbody>
</table>

Assuming:
- $B(\Xi^{-}\rightarrow\Xi^{-}\gamma) = \frac{3}{2} B(\Lambda^{0}_{b}\rightarrow \Lambda \gamma)$ (as for dimuonic channels)
- Theoretical prediction
Introduction: Meson decays

Radiative b-meson decays:

- Can oscillate
- SV can be determined from resonances decays
- Quite studied (lot of experience)
- Large production
- Accessible at B-factories
Sensitivity to photon polarization

Sensitivity to the photon polarization in the $\Lambda_b \rightarrow \Lambda \gamma$ decay using angular distribution [EPJC(2019)79:634]:

- **Statistical uncertainty**: Goes as $1/\sqrt{N}$ with number of events
- **Resolution**: Effect neglible
- **Acceptance**: Asymmetric in $\alpha_{\gamma}$
- **Background**: Important dilution
Simultaneous Mass fit: Validation

Mass fit validated through MC Study:

- 1000 pseudo-experiments
- Testing $\mathcal{B}(\Xi_b^- \rightarrow \Xi^-\gamma)$ hypotheses in range $(10^{-5}, 10^{-3})$
- Measurement significance using Wilk’s theorem

<table>
<thead>
<tr>
<th>$\mathcal{B}(\Xi_b^- \rightarrow \Xi^-\gamma)$</th>
<th>Evidence Prob [%] ($\sigma \geq 3$)</th>
<th>Observation Prob [%] ($\sigma \geq 5$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 10^{-3}$</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>$5 \times 10^{-4}$</td>
<td>100.0</td>
<td>98.0</td>
</tr>
<tr>
<td>$3.3 \times 10^{-4}$</td>
<td>96.7</td>
<td>57.1</td>
</tr>
<tr>
<td>$1 \times 10^{-4}$</td>
<td>26.2</td>
<td>0.8</td>
</tr>
<tr>
<td>$5 \times 10^{-5}$</td>
<td>5.5</td>
<td>0.0</td>
</tr>
<tr>
<td>$1.1 \times 10^{-5}$</td>
<td>0.9</td>
<td>0.0</td>
</tr>
</tbody>
</table>
MC-Toys result (S=197, B=412): $\alpha_\gamma$

\[
\begin{align*}
\mu &= 0.985 \pm 0.008 \\
\sigma &= 0.305 \pm 0.005
\end{align*}
\]
Amplitud Model

Helicity formalism + isobar lineshape in $m_{pK}$

Amplitude for a defined set of helicities in $\Lambda_b \rightarrow \Lambda^* (\rightarrow pK)\gamma$

$D_{(\Lambda^* - \Lambda)} M_{\Lambda_b} (\varphi_{\Lambda} \theta_{\Lambda} - \varphi_{\Lambda}) D_{\Lambda_p \Lambda} (\varphi_{p} \theta_{p} - \varphi_{p})$

$J_{\Lambda_b}^{L_{\Lambda_b} - S_{\Lambda_b}} \sum_{S=|J_{\Lambda_b} - J_{\Lambda}|} \sum_{L=|J_{\Lambda_b} + S_{\Lambda_b}|} \left[ C_1 C_2 C_3 \text{Clebsch-Gordans} \right]

\text{fit parameter } h_{LS} \left( \frac{p}{M_{\Lambda_b}} \right)^L \left( \frac{q}{M_{\Lambda}} \right)^I

B_L(p) B_I(q) X(m_{pK}) \text{ lineshape}

To obtain full decay rate

Coherently sum possible $\Lambda^*$ helicities and $\Lambda^*$ resonances
Incoherently sum possible proton, photon, and $\Lambda_b$ helicities

To check for pentaquarks in $m_{p\gamma}$

Need for second decay chain amplitude
Non-trivial relation between the decay planes of $\Lambda_b \rightarrow \Lambda^* (\rightarrow pK)\gamma$ and $\Lambda_b \rightarrow P_c (\rightarrow p\gamma)K$
Mass fit and Dalitz plot

- **Signal**: Bifurcated Crystal Ball
- **Background**:
  - Combinatorial: Exponential
  - Partially reconstructed: Argus convoluted with signal shape
- **Tails parameters fixed in MC**
Photon polarization has only been measured using radiative $b$-meson decays:

**Proper time distribution:**
- $B - \overline{B}$ interference:
  - $B_s \rightarrow \phi \gamma$,  
  - [PRL118('17)109901]

**Angular distribution:**
- $B^+ \rightarrow K^- \pi^+ \pi^+ \gamma$,  
  - [PRL 112('14)161801]
- $B \rightarrow K^* e^+ e^-$ at low $q^2$,  
  - [JHEP04('15)064]
Angular distribution: $\Xi_b^- \rightarrow \Xi^- \gamma$

Angular distribution for unpolarized $\Xi_b^-$ decay (integrating on azimuthal angles):

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

The values of the decay parameters are:

- $\alpha_\Xi = -0.401 \pm 0.010$ [PDG 2020]
- $\alpha_\Lambda = 0.732 \pm 0.010$ [PDG 2020]

Advantages of $\Xi_b^-$ over $\Lambda_b$

- Extra decay $\implies$ richer angular distribution
- Charged particle: $\Xi^-$