Radiative B decays at LHCb

Carla Marin
on behalf of the LHCb Collaboration

11th International Workshop on the CKM Unitarity Triangle
November 2021
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(some results with $b$-baryons!)
Why radiative $b$ decays?

- FCNC sensitive to indirect effects of New Physics (NP) in loops
  - branching fractions, CPV, photon polarisation, etc.
- Access to much larger scales than direct searches
Radiative b-decay observables

\[ \mathcal{H}_{\text{eff}} \propto V_{ts}^* V_{tb} (C_7 O_7 + C'_7 O'_7) \]

Branching ratios
\[ |C_7|^2 + |C'_7|^2 \]

CP asymmetries
\[ \text{Im}(C_7) \]

Photon polarisation
\[ C'_7 \]
New Physics constraints from \( b \to s \gamma \)

Paul & Straub [JHEP04(2017)027]

\[ \text{Im } \Delta C_7(\mu_b) = -0.027 \pm 0.016 \text{ for } B^0 \to K^* \gamma \]
The LHCb detector

\[ \frac{\Delta p}{p} = 0.5 - 1.0\% \]

\[ \Delta \text{IP} = (15 + 29/p_T[^{\text{GeV}}]) \mu m \]

\[ \frac{\Delta E}{E_{\text{ECAL}}} = 1\% + 10\% / \sqrt{E[^{\text{GeV}}]} \]

Electron ID ~90% for ~5% e\(\rightarrow\)h mis-id probability

Kaon ID ~95% for ~5% \(\pi\rightarrow\)K mis-id probability
LHCb dataset

All b-hadron species!

- $B_s: \frac{f_s}{f_d+f_u} = 0.259 \pm 0.018$
- $\Lambda_b: \frac{f_{\Lambda_b}}{f_d+f_u} = 0.122 \pm 0.006$

average in LHCb acceptance [PRD100(2019)031102]

and more: $\Xi_b'$, $\Omega_b'$, $B_c'$, $B^*$ ...

Total recorded luminosity $\sim 9$ fb$^{-1}$:

- Run 1 (2011-2012) $\sim 3$ fb$^{-1}$
- Run 2 (2015-2018) $\sim 6$ fb$^{-1}$ and $\sigma_b (13\text{TeV})/\sigma_b (7\text{TeV}) \sim 2$ [JHEP1712(2017)026]
Recent LHCb results

Since the last CKM workshop:

- **First observation of the radiative decay** $\Lambda^0_b \to \Lambda \gamma$ [PRL123(2019)031801]
- **Measurement of CP-violating and mixing-induced observables in** $B_s \to \Phi \gamma$ decays [PRL123(2019)081802]
- Strong constraints on the $b \to s \gamma$ photon polarisation from $B^0 \to K^* e^+ e^-$ decays [IHEP12(2020)081]
- **Search for the radiative** $\Xi^-_b \to \Xi^- \gamma$ decays [arXiv:2108.07678]
- Analysis of neutral B-meson decays into two muons [arXiv:2108.09283]
- **Measurement of the photon polarization in** $\Lambda^0_b \to \Lambda \gamma$ decays [arXiv:2111.10194]

See talk by M. Kreps for photon polarisation from $B^0 \to K^* e^+ e^-$
See talk by F. Dettori for first limit on $B_s \to \mu^+ \mu^- \gamma$ decays
Photon polarization in $B_s \rightarrow \phi \gamma$

Time dependent decay rate for $f_{CP}$ states gives access to photon polarization:

$$\Gamma(t) \propto e^{-\Gamma_{st}t} \left[ \cosh \left( \frac{\Delta \Gamma(s)}{2} \right) - A^\Delta \sinh \left( \frac{\Delta \Gamma(s)}{2} \right) \pm C_{CP} \cos \left( \Delta m_{(s)}t \right) \mp S_{CP} \sin \left( \Delta m_{(s)}t \right) \right]$$

Accessible from decay time distribution

Require knowledge of the $B_s$ flavour at production

$A_{\phi\gamma}^\Delta \approx \frac{\text{Re}(e^{-i\phi_s} C_7 C'_7)}{|C_7|^2 + |C'_7|^2}$

$S_{\phi\gamma} \approx \frac{\text{Im}(e^{-i\phi_s} C_7 C'_7)}{|C_7|^2 + |C'_7|^2}$
Photon polarization in $B_s \rightarrow \phi\gamma$

- Fit to time-dependent decay rate using full Run 1 data (3 fb$^{-1}$):

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

Compatible with SM and previous result for $A^\Delta$

First measurement in $B_s$ system
First observation of $\Lambda^0_b \rightarrow \Lambda \gamma$

Baryonic $b \rightarrow s\gamma$ not prev. observed
BR $< 1.9 \cdot 10^{-3}$ [CDF PhysRevD.66.112002]

Very challenging topology $\rightarrow$
dedicated reconstruction in Run 2

$\Lambda_b \{\begin{array}{c}
| b & s \\
| d & d \\
| u & u \\
\end{array} \} \Lambda(1115)$

BR$_{SM} \in [0.06, 1] \times 10^{-5}$ [Wang et al., Mannel et al., Gan et al., Faustov et al.]

Gives access to photon polarisation
[Mannel & Recksiegel, Hiller & Kagan]

Huge combinatorial background mitigated with performant MVA

PRL 123 031801 (2019)
First observation of $\Lambda^0_{b} \rightarrow \Lambda \gamma$

Using 2016 dataset (1.7 fb$^{-1}$)

Significance of 5.6$\sigma$ \rightarrow First observation!

Normalising to the well-known $B^0 \rightarrow K^* \gamma$:

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

statistically dominated; main systematic from production fraction
Proton helicity gives access to the photon polarisation [Mannel & Recksiegel, Hiller & Kagan]:

\[
\alpha_\gamma = \frac{P(\gamma_L) - P(\gamma_R)}{P(\gamma_L) + P(\gamma_R)}
\]

\[
\alpha_\gamma = \frac{1-|r|^2}{1+|r|^2}
\]

\[
\mathcal{R}^{LO} = \frac{C'_7}{C_7} \sim \frac{m_s}{m_b} \text{ in SM}
\]

\[
\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda b} \cos\theta_\gamma
\]

\[
\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,1/2} \cos\theta_p
\]

Sensitive to right handed currents

\( P_{\Lambda b} \) consistent with 0 [JHEP 06 (2020) 110]

\( \alpha_{p,1/2} = (0.750 \pm 0.009) \) [Nature Phys. 15(2019)631-634]
Photon polarisation in $\Lambda^0_{b} \rightarrow \Lambda \gamma$

Uses full Run 2 dataset (6 fb$^{-1}$) and reoptimised selection

Fit signal and background angular distributions in signal mass region, main systematic from background shape
Photon polarisation in $\Lambda_b^0 \rightarrow \Lambda\gamma$

Confidence interval in physical region obtained through Feldman-Cousins

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

$$\alpha_\gamma = 0.82^{+0.17}_{-0.26} \ (\text{stat.})^{+0.04}_{-0.13} \ (\text{syst.})$$
Photon polarisation in $\Lambda^0_b \rightarrow \Lambda\gamma$

Confidence interval in physical region obtained through Feldman-Cousins

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

First measurement of the $b \rightarrow s\gamma$ photon polarisation in $b$-baryon decays!
Photon polarisation in $\Lambda^0_b \rightarrow \Lambda\gamma$

CPV measurement by splitting the sample according to the $p$ charge:

$$\alpha^- > 0.56 (0.44) \text{ at } 90\% (95\%) \text{ CL},$$

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

arXiv:2111.10194
Photon polarisation in $\Lambda^0_b \to \Lambda\gamma$

New constraints on $C_7$ and $C'_7$: discard 2 so-far allowed solutions

CPV results not included: need theory input (and better precision)
Search for $\Xi^-_b \rightarrow \Xi^- \gamma$ decays

No previous search. SM predictions:

- $\text{BR}_{\text{SM}} = (3.03 \pm 0.10) \times 10^{-4}$ \cite{Liu et al., '11} based on LCSR - rather high for a radiative decay
- $\text{BR}_{\text{SM}} = (1.23 \pm 0.64) \times 10^{-5}$ \cite{Wang et al., '20} based on measured $\text{BR}(\Lambda_b \rightarrow \Lambda^0 \gamma) + \text{SU}(3)$

Very challenging topology at LHCb, only 5% decay in the vertex locator
Search for $\Xi^{-}_b \rightarrow \Xi^{-} \gamma$ decays

Uses Run 2 data (5.4 fb$^{-1}$) and $\Xi^{-}_b \rightarrow \Xi^{-} J/\psi$ as control mode

No signal found $\rightarrow$ limit from Feldman-Cousins

- dominated by systematic from $\text{BR}(\Xi^{-}_b \rightarrow \Xi^{-} J/\psi)$

$\text{BR}(\Xi^{-}_b \rightarrow \Xi^{-} \gamma) < 1.3(0.6) \times 10^{-4}$ at 95% (90%) CL

$\text{BR}(\Xi^{-}_b \rightarrow \Xi^{-} \gamma) / \text{BR}(\Xi^{-}_b \rightarrow \Xi^{-} J/\psi) < 0.12 (0.08)$ at 95% (90%) CL

arXiv:2108.07678
Conclusions

LHCb is a b-hadron factory: access to radiative decays of all hadron species

- most precise $B_s \rightarrow \phi \gamma$ results
- first measurement of photon polarisation in baryon $b \rightarrow s \gamma$ decays

Precision era in $b \rightarrow s \gamma$ measurements:

- world-best constraints on $C'_7$
Future prospects

Decay mode | Upgrade 2 (300 fb⁻¹)
--- | ---
\(B_s \rightarrow \phi \gamma\) | \(\delta A^\Delta \sim 0.02\)
\(\Lambda^0_b \rightarrow \Lambda \gamma\) | \(\delta \alpha_\gamma \sim 4\%\)
\(\Xi^-_b \rightarrow \Xi \gamma\) | \(\delta \alpha_\gamma \sim 10\%\)
\(B^+ \rightarrow K^+\pi^+\pi^-\gamma\) | \(\delta \alpha_\gamma \sim 1\%\)
\(B^0 \rightarrow K^-e^+e^-\) | \(\delta A_T^{(2)} \sim 2\%\)

+ modes with more neutrals, eg \(B^0 \rightarrow K_S\pi^+\pi^-\gamma\)
+ \(b \rightarrow \text{d}y\) decays

Good control of systematic uncertainties will be critical
Future prospects

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Upgrade 2 (300 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \to \phi \gamma$</td>
<td>$\delta A^A \sim 0.02$</td>
</tr>
<tr>
<td>$\Lambda^0_{b} \to \Lambda \gamma$</td>
<td>$\delta \alpha_\gamma \sim 4%$</td>
</tr>
<tr>
<td>$\Xi^-_{b} \to \Xi \gamma$</td>
<td>$\delta \alpha_\gamma \sim 10%$</td>
</tr>
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<td>$B^+ \to K^+\pi^+\pi^-\gamma$</td>
<td>$\delta \alpha_\gamma \sim 1%$</td>
</tr>
<tr>
<td>$B^0 \to K^{-}e^+e^-$</td>
<td>$\delta A_T^{(2)} \sim 2%$</td>
</tr>
</tbody>
</table>

+ modes with more neutrals, eg $B^0 \to K_S\pi^+\pi^-\gamma$ + $b \to d\gamma$ decays

Good control of systematic uncertainties will be critical

Stay tuned!
Thanks for the attention

Questions?
Comments?
BACK-UP
$\Lambda_b \rightarrow \Lambda^0\gamma$: acceptance and background
$\Lambda_b \rightarrow \Lambda^0\gamma$: CP mass fits
Exploiting $b \rightarrow s e^+ e^-$ at very low $q^2$

Angular coefficients $A_T^{(2)}$ and $A_T^{\text{Im}}$ give access to $C'_7$:

$$\frac{1}{d(\Gamma + \Gamma)/dq^2} \frac{d^4(\Gamma + \Gamma)}{dq^2 dcos \theta_{\ell} dcos \theta_K d\phi} =$$

$$= \frac{9}{16\pi} \left[ \frac{3}{4}(1 - F_L)\sin^2 \theta_K + F_L \cos^2 \theta_K + \right.$$  

$$\left. \left( \frac{1}{4}(1 - F_L)\sin^2 \theta_K - F_L \cos^2 \theta_K \right) \cos 2\theta_{\ell} + \right.$$  

$$\frac{1}{2}(1 - F_L)A_T^{(2)}\sin^2 \theta_K \sin^2 \theta_{\ell} \cos 2\phi + (1 - F_L)A_T^{\text{Re}}\sin^2 \theta_K \cos \theta_{\ell} +$$  

$$\frac{1}{2}(1 - F_L)A_T^{\text{Im}}\sin^2 \theta_K \sin^2 \theta_{\ell} \sin 2\phi \right].$$

Pollution from $C_{9,10}$ when $q^2$ far from zero → analysis at very low $q^2$

- Run 1 analysis: $q^2 \in [0.002, 1.120]$ GeV$^2/c^4$
- Run 1+2: $q^2 \in [0.0008, 0.257]$ GeV$^2/c^4$

after folding $\Phi$ to reduce number of parameters
Exploiting $b \rightarrow s e^+ e^-$ at very low $q^2$

Much cleaner selection achieved in new analysis

Mass shape, angular acceptance and model validated with $B \rightarrow K^* \gamma (\rightarrow e^+ e^-)$
Exploiting $b \rightarrow s e^+ e^-$ at very low $q^2$

Word-best constraints on $C'_7$ achieved!

\[
\begin{align*}
F_L &= 0.044 \pm 0.026 \pm 0.014, \\
A_{T}^{Re} &= -0.06 \pm 0.08 \pm 0.02, \\
A_{T}^{(2)} &= +0.11 \pm 0.10 \pm 0.02, \\
A_{T}^{Im} &= +0.02 \pm 0.10 \pm 0.01,
\end{align*}
\]

Perfect agreement with SM

still room for NP?
LHCb Trigger

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

LO Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu$
- 150 kHz $e/\gamma$

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage
Flavour tagging at LHCb
LHCb Upgrade for photon polarisation

Projections with 300 fb$^{-1}$, assuming same performances as Run 1/2

by C. Sánchez