Radiative B decays at LHCb

Carla Marin

on behalf of the LHCb Collaboration

11th International Workshop on the CKM Unitarity Triangle

November 2021

b (several results with b-baryons!)

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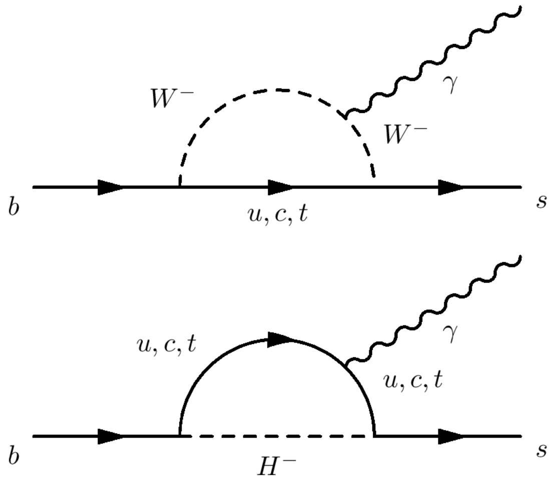
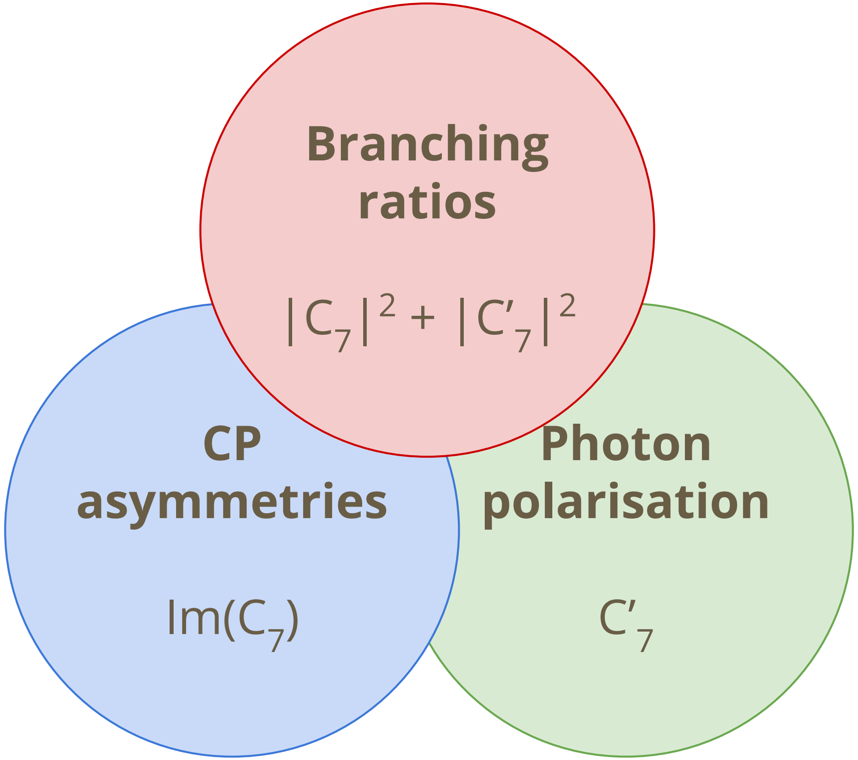
Why radiative b decays?

- 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



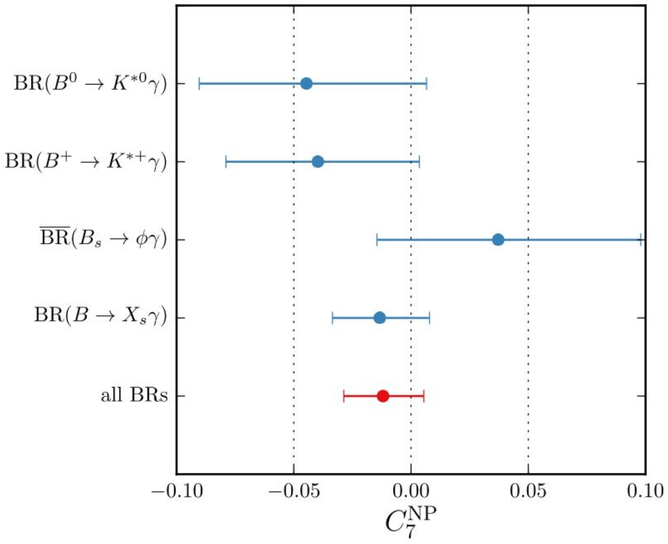
Radiative b-decay observables

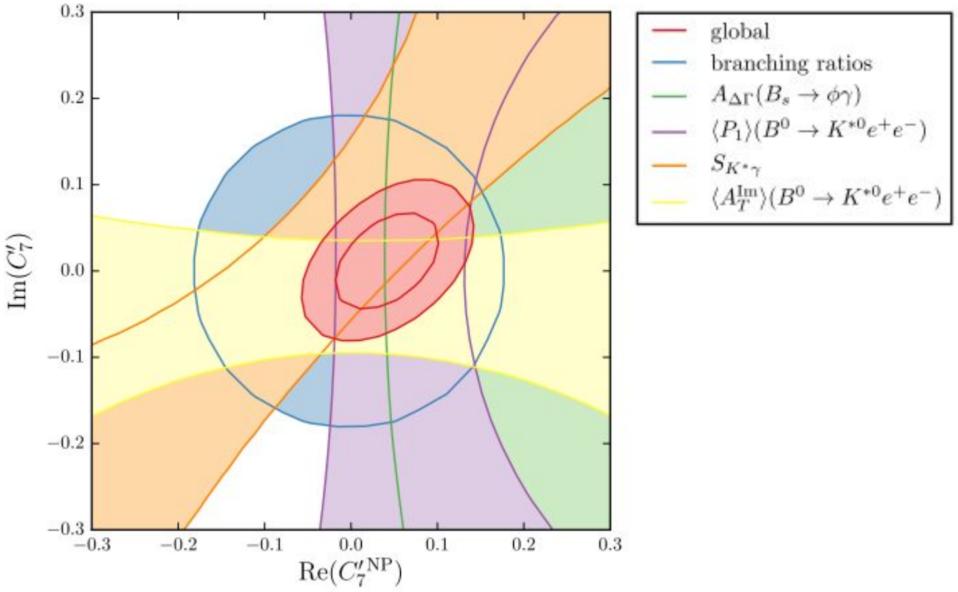
$$\mathcal{H}_{eff} \propto V_{ts}^* V_{tb} (C_7 O_7 + C_7' O_7')$$



New Physics constraints from b⟶sγ

Paul & Straub [JHEP04(2017)027]

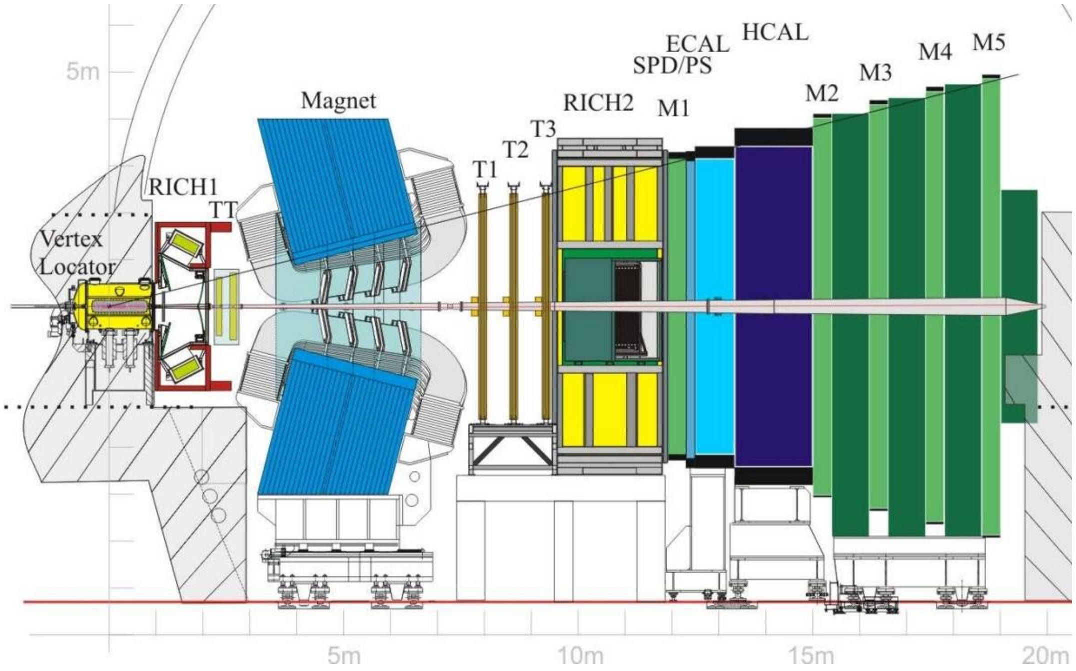




$$\boxed{\mathrm{Im}\,\Delta C_7(\mu_b) = -0.027 \pm 0.016 \qquad \text{for } B^0 \to K^*\gamma}$$

JINST 3 (2008) S08005

The LHCb detector



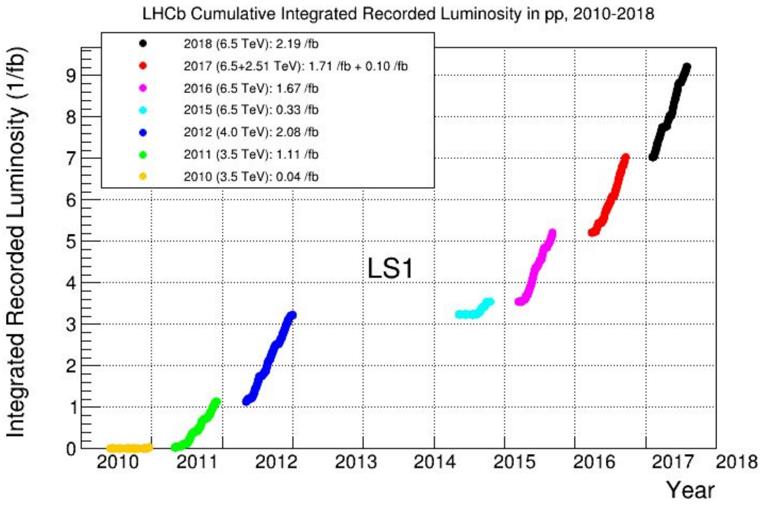
$\Delta p / p = 0.5 - 1.0\%$
$\Delta IP = (15 + 29/p_T[\mathrm{GeV}])\ \mu m$

$\Delta E/E_{ECAL} = 1\% + 10\% / \sqrt{(E[\mathrm{GeV}])}$

Electron ID ~90% for ~5% e→h mis-id probability

Kaon ID ~ 95 % for ~ 5 % π→K mis-id probability

LHCb dataset



All b-hadron species!

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

average in LHCb acceptance [PRD100(2019)031102]

and more: Ξ_b, Ω_b, B_c, B^* ...

Total recorded luminosity ~9 fb^{-1}:

- Run 1 (2011-2012) ~ 3 fb^{-1}
- Run 2 (2015-2018) ~ 6 fb^{-1} and σ_b(13TeV)/σ_b(7TeV) ~ 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 [JHEP12(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 $B_s \rightarrow \phi\gamma$

PRL 123 (2019) 081802

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

$$\Gamma(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_{(s)}}{2}\right) - \mathcal{A}^{\Delta}\sinh\left(\frac{\Delta\Gamma_{(s)}}{2}\right) \pm \mathcal{C}_{CP}\cos\left(\Delta m_{(s)}t\right) \mp \mathcal{S}_{CP}\sin\left(\Delta m_{(s)}t\right)\right]$$

Accessible from decay time distribution

PRL 118(2017)2,021801

Require knowledge of the B_s flavour at production

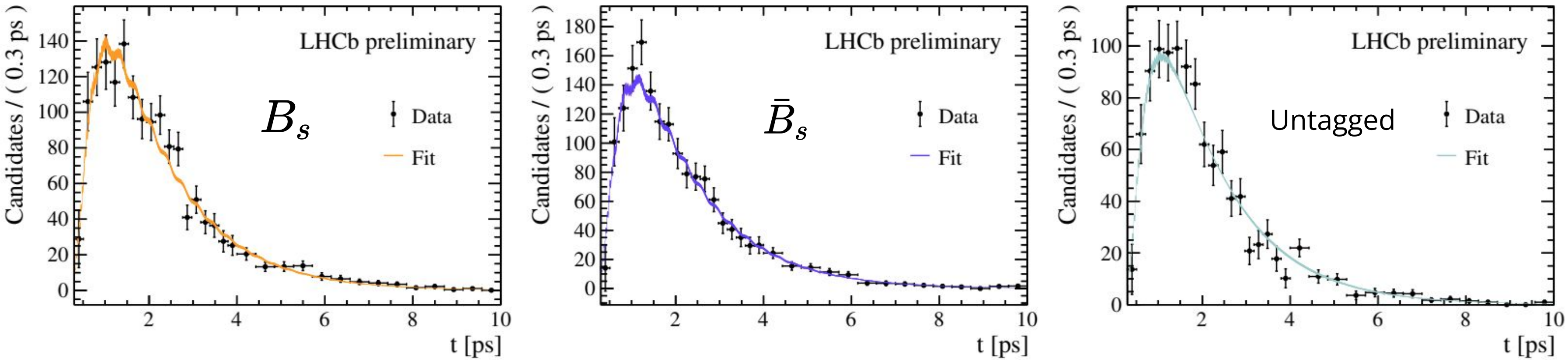
PRL 123 (2019) 081802

$$\boxed{\mathcal{A}^{\Delta}_{\phi\gamma} \simeq \frac{\mathrm{Re}(e^{-i\phi_s}C_7C_7')}{|C_7|^2+|C_7'|^2} \quad S_{\phi\gamma} \simeq \frac{\mathrm{Im}(e^{-i\phi_s}C_7C_7')}{|C_7|^2+|C_7'|^2}}$$

Photon polarization in $B_s \to \phi\gamma$

PRL 123 (2019) 081802

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



$$\boxed{\begin{aligned} S_{\phi\gamma} &= 0.43 \pm 0.30 \pm 0.11 \\ C_{\phi\gamma} &= 0.11 \pm 0.29 \pm 0.11 \\ \mathcal{A}^{\Delta}_{\phi\gamma} &= -0.67\,^{+0.37}_{-0.41} \pm 0.17 \end{aligned}}$$

First measurement in B_s system

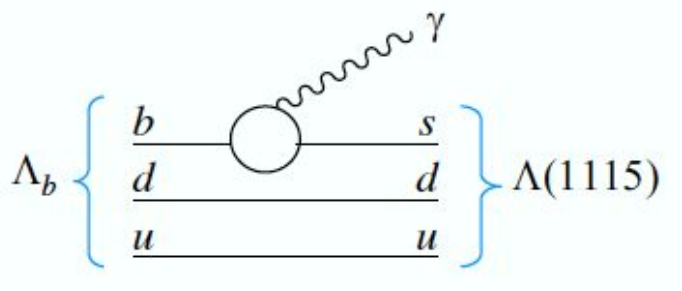
Compatible with SM and previous result for A^{Δ}

First observation of $\Lambda^0_b \to \Lambda\gamma$

PRL 123 031801 (2019)

Baryonic $b \to s\gamma$ not prev. observed

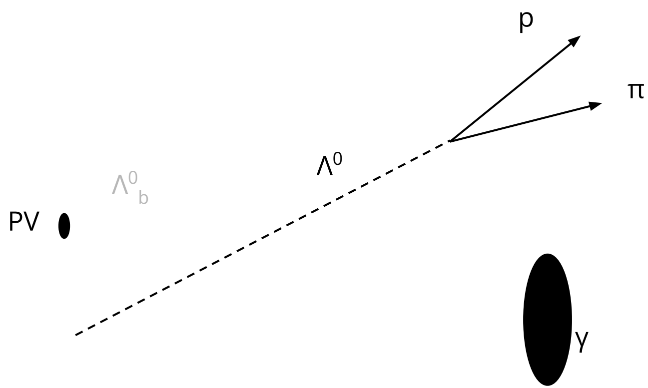
BR < $1.9 \cdot 10^{-3}$ [CDF PhysRevD.66.112002]



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

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

Very challenging topology → dedicated reconstruction in Run 2



Huge combinatorial background mitigated with performant MVA

First observation of $\Lambda^0_b \to \Lambda\gamma$

PRL 123 031801 (2019)

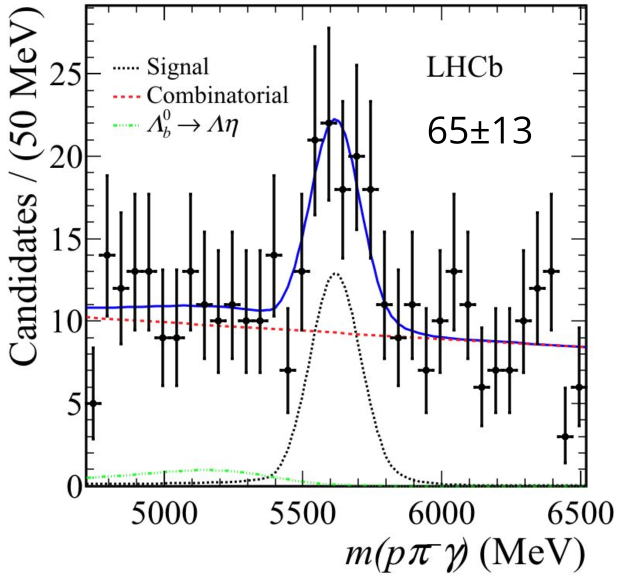
Using 2016 dataset (1.7 fb^{-1})

Significance of 5.6σ → First observation!

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

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

statistically dominated; main systematic from production fraction



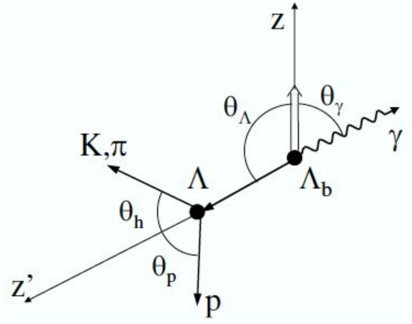
Photon polarisation in $\Lambda^0_b \to \Lambda\gamma$

Proton helicity gives access to the photon polarisation [Mannel & Recksiegel, Hiller & Kagan]:

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

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

$$r^{LO} = \frac{C_7'}{C_7} \sim \frac{m_s}{m_b} \text{ in SM}$$



$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_{\Lambda_b} \cos\theta_\gamma$$

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

Sensitive to right handed currents

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

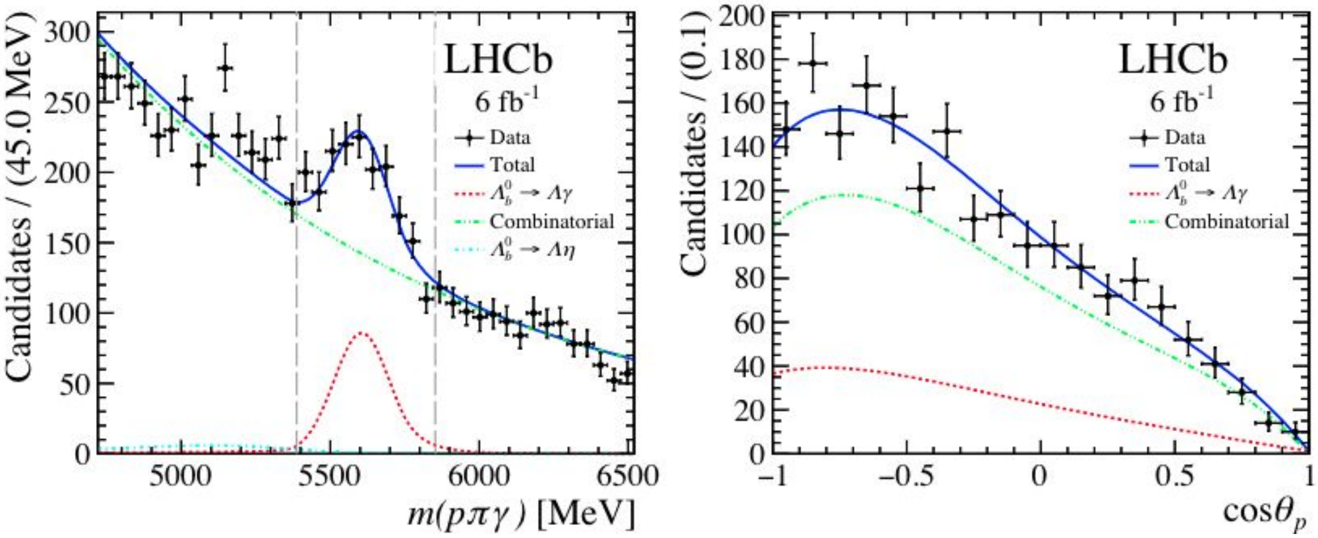
$\alpha_{p,½}$= (0.750 ± 0.009) [Nature Phys.15(2019)631-634]

Photon polarisation in $\Lambda^0_b \to \Lambda\gamma$

arXiv:2111.10194

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

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

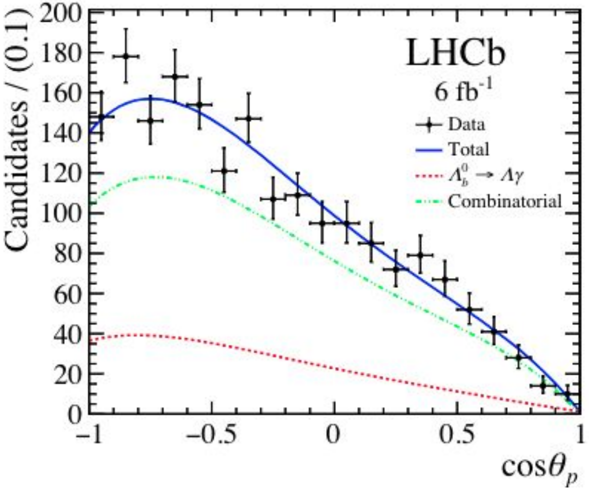


Fit signal and background angular distributions in signal mass region, main systematic from background shape

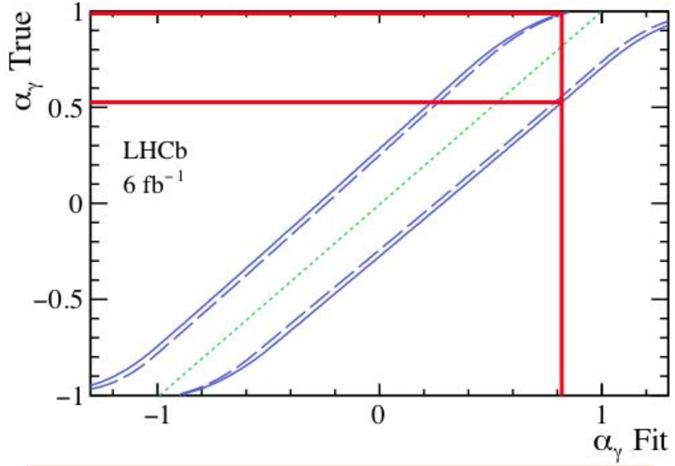
Photon polarisation in $\Lambda^0_b \to \Lambda\gamma$

arXiv:2111.10194

Confidence interval in physical region obtained through Feldman-Cousins



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

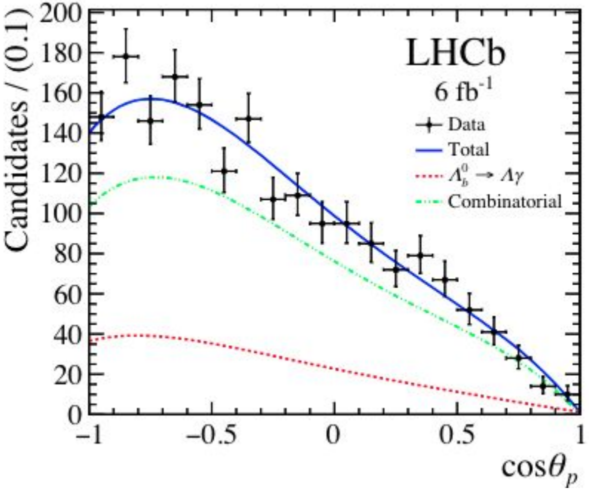


$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\ (\text{stat.})\ ^{+0.04}_{-0.13}\ (\text{syst.})$$

Photon polarisation in $\Lambda^0_b \to \Lambda\gamma$

arXiv:2111.10194

Confidence interval in physical region obtained through Feldman-Cousins



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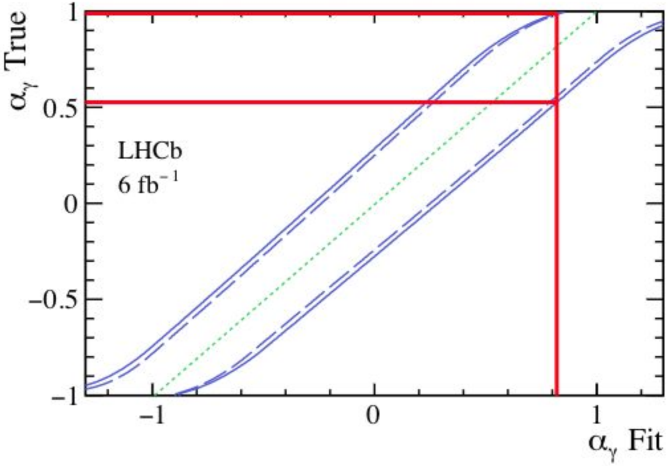


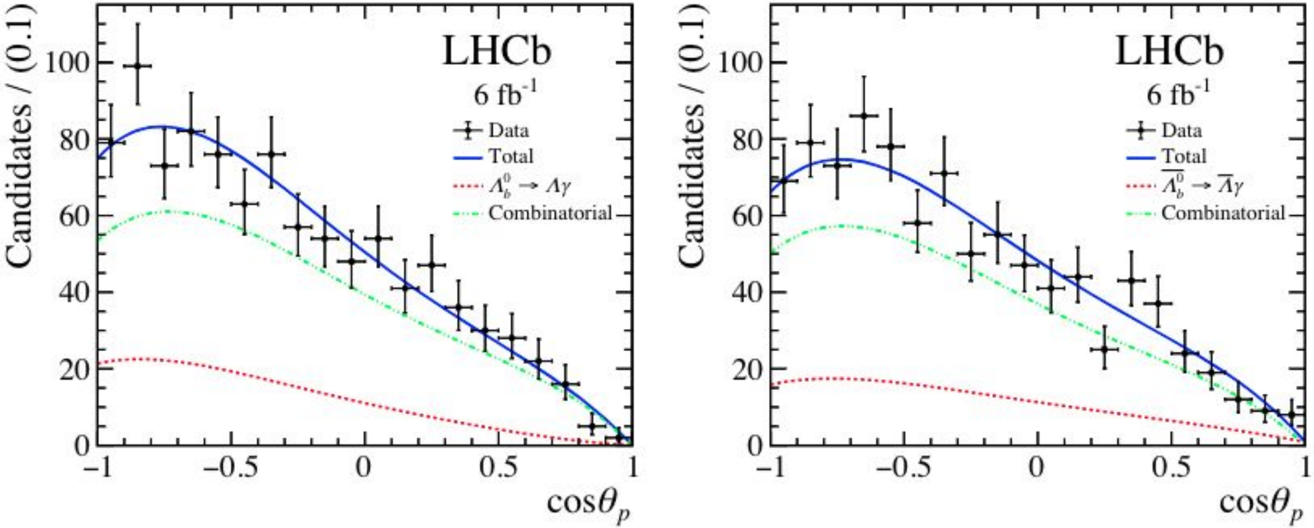
$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\ (\text{stat.})^{+0.04}_{-0.13}\ (\text{syst.})$$

First measurement of the b→ s γ photon polarisation in b-baryon decays!

Photon polarisation in $\Lambda^0_b \to \Lambda\gamma$

arXiv:2111.10194

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

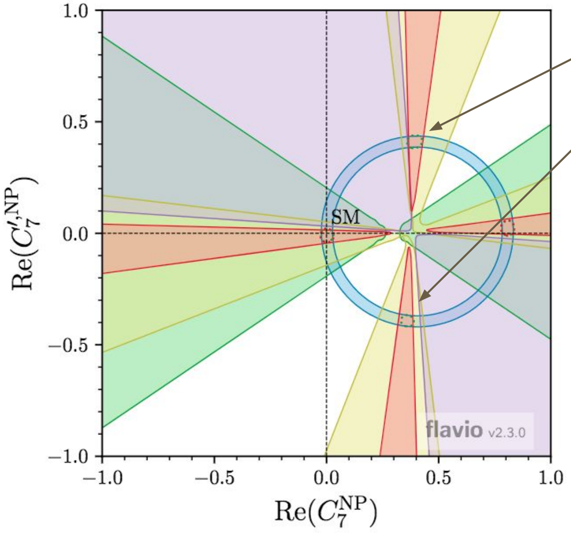


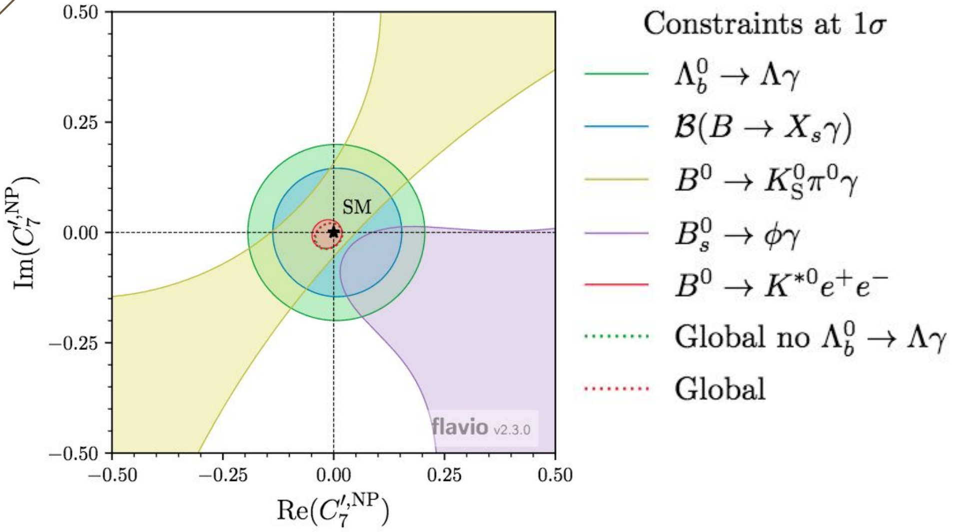
$$\alpha_\gamma^- \; > \; 0.56\ (0.44) \text{ at } 90\%\ (95\%) \text{ CL}, \qquad \alpha_\gamma^+ \; = \; -0.56^{\,+0.36}_{\,-0.33}\ (\text{stat.})^{\,+0.16}_{\,-0.09}\ (\text{syst.}),$$

Photon polarisation in $\Lambda^0_b \to \Lambda\gamma$

arXiv:2111.10194

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





CPV results not included: need theory input (and better precision)

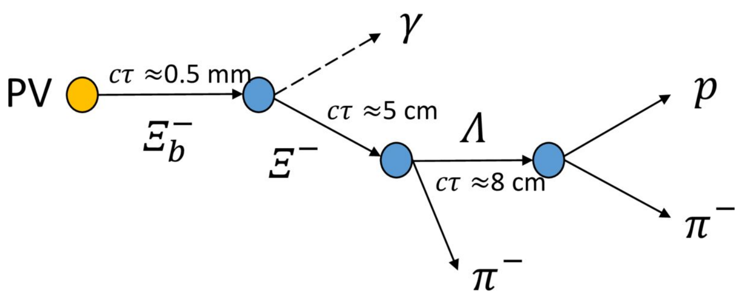
Search for $\Xi_b^- \to \Xi^- \gamma$ decays

arXiv:2108.07678

No previous search. SM predictions:

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

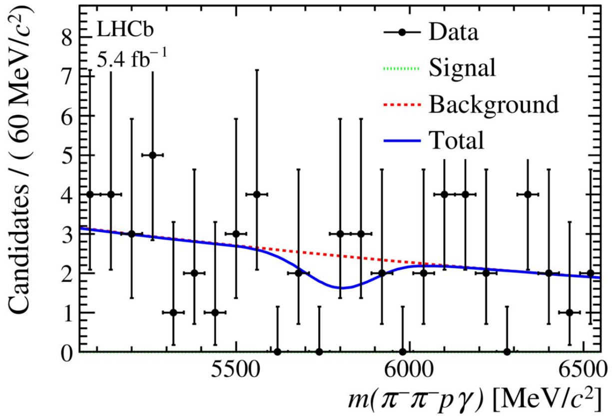
Very challenging topology at LHCb, only 5% decay in the vertex locator

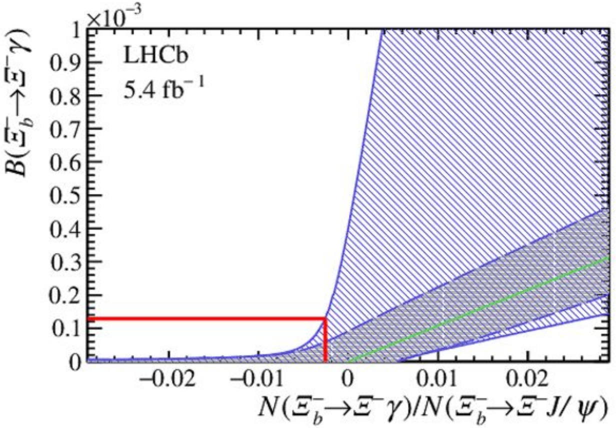


Search for $\Xi^-_b \to \Xi^-\gamma$ decays

arXiv:2108.07678

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





No signal found → limit from Feldman-Cousins

- dominated by systematic from BR($\Xi^-_b \to \Xi^- J/\psi$)

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

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

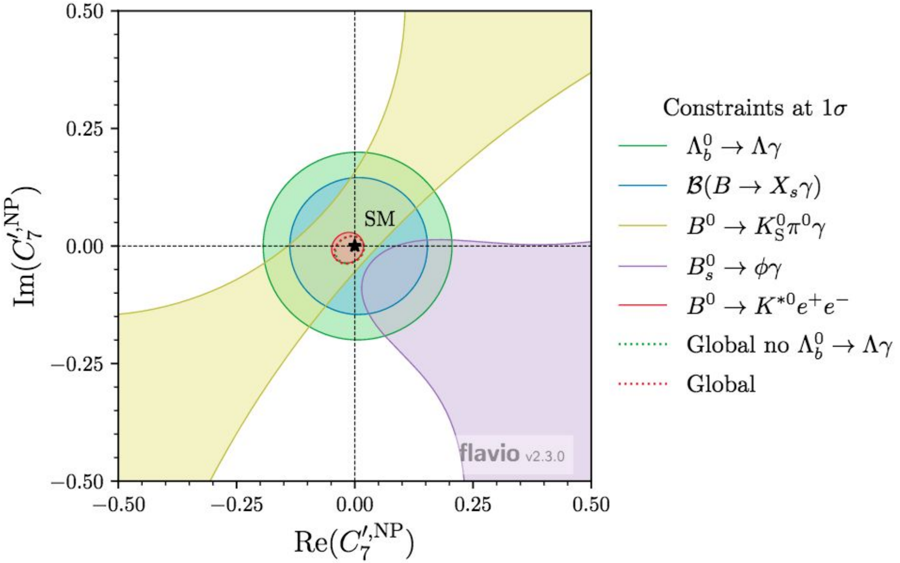
Conclusions

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

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

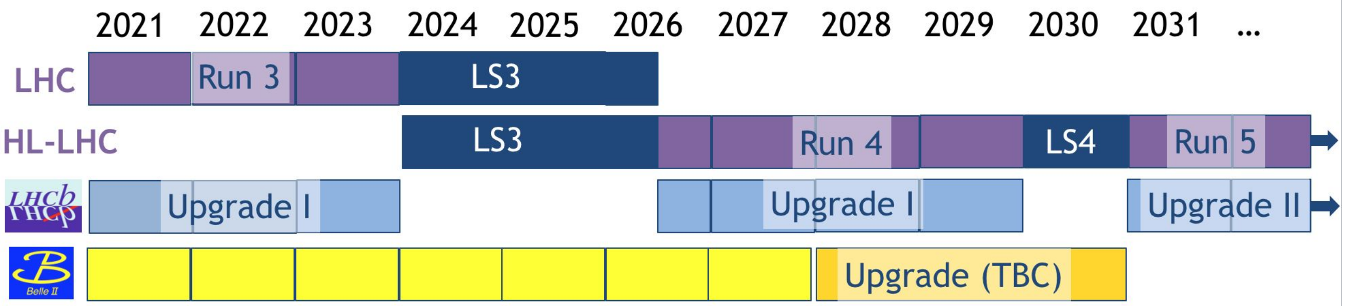
Precision era in $b \to s\gamma$ measurements:

- world-best constraints on C'_7



LHCB-PUB-2018-009

Future prospects



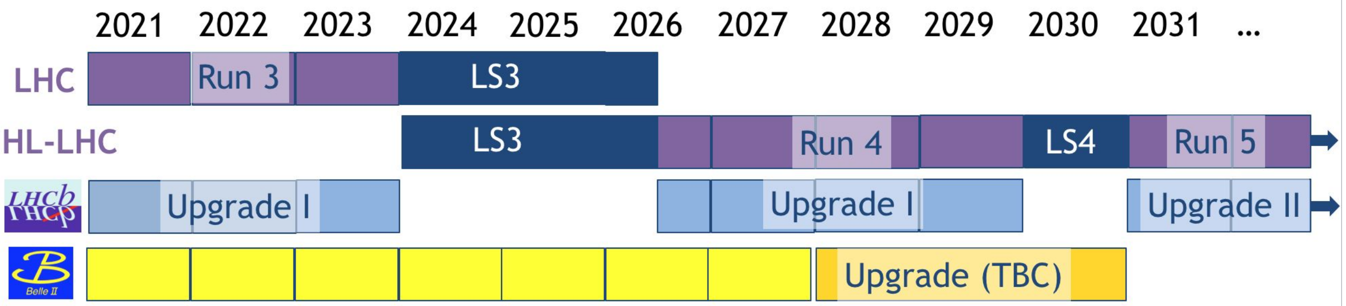
Decay mode	Upgrade 2 (300 fb^{-1})
$B_s \to \phi\gamma$	$\delta A^{\Delta} \sim 0.02$
$\Lambda^0_b \to \Lambda\gamma$	$\delta\alpha_\gamma \sim 4\%$
$\Xi^-_b \to \Xi^-\gamma$	$\delta\alpha_\gamma \sim 10\%$
$B^+ \to K^+\pi^+\pi^-\gamma$	$\delta\alpha_\gamma \sim 1\%$
$B^0 \to K^* e^+ e^-$	$\delta A_T^{(2)}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

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

Good control of systematic uncertainties will be critical

LHCB-PUB-2018-009

Future prospects



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$\Xi^-_b \to \Xi^-\gamma$	$\delta\alpha_\gamma \sim 10\%$
$B^+ \to K^+\pi^+\pi^-\gamma$	$\delta\alpha_\gamma \sim 1\%$
$B^0 \to K^*e^+e^-$	$\delta A_T^{(2)} \sim 2\%$

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

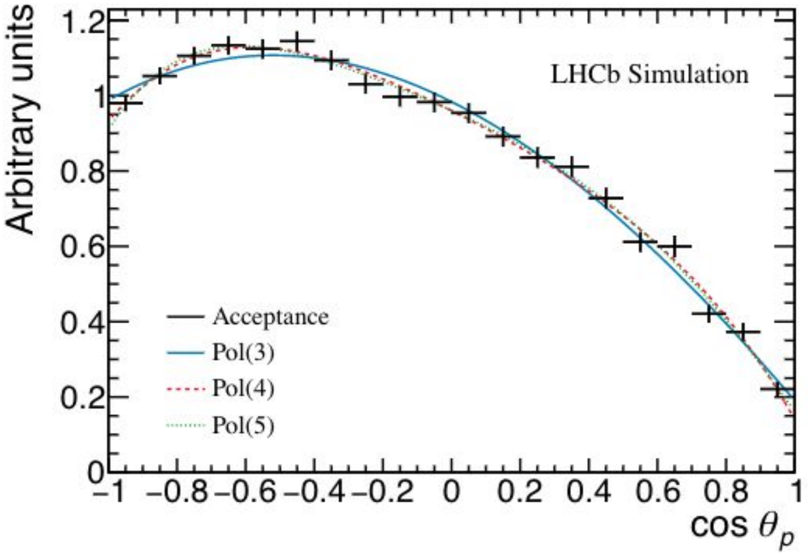
Good control of systematic uncertainties will be critical

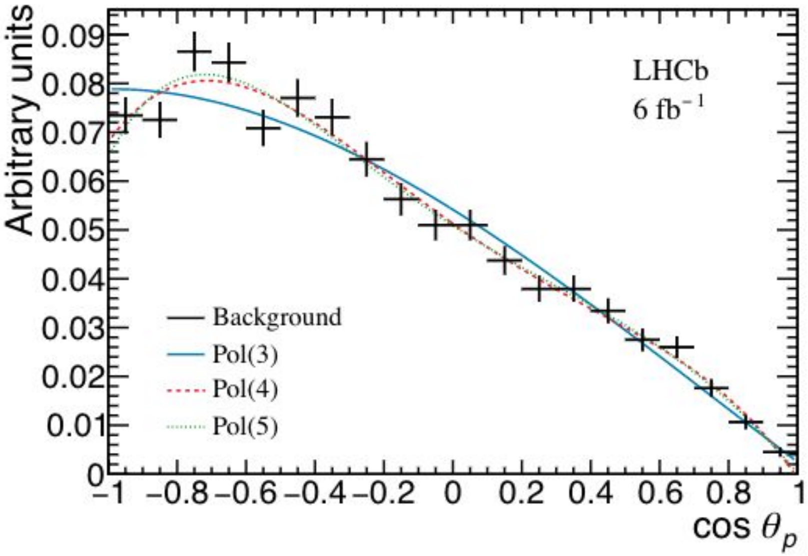
Stay tuned!

Thanks for the attention

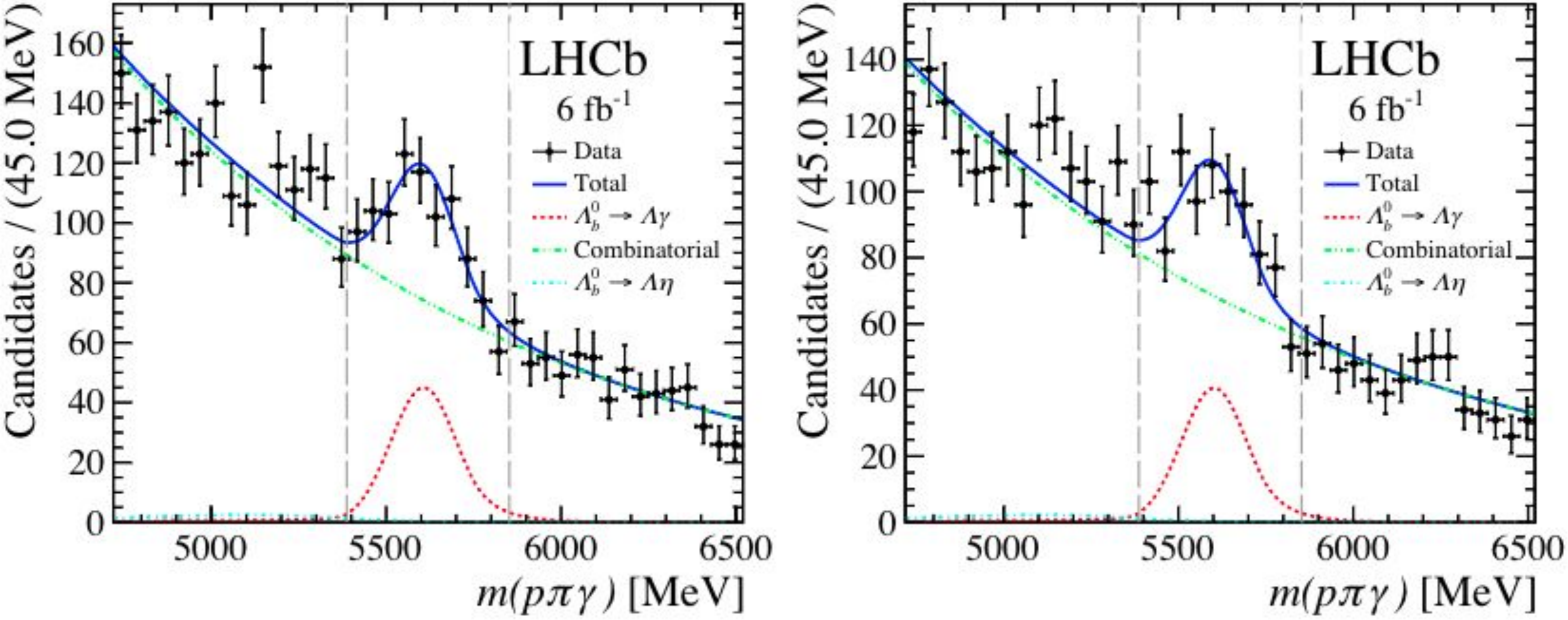
BACK-UP

$\Lambda_b \rightarrow \Lambda^0\gamma$: acceptance and background





$\Lambda_b \rightarrow \Lambda^0\gamma$: CP mass fits



Exploiting b⟶se$^+$e$^-$ at very low q^2

JHEP 04 (2015) 064
arXiv:2010.06011

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

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

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

after folding Φ to reduce number of parameters

$$\boxed{A_\mathrm{T}^{(2)}(q^2\to 0) = \frac{2\mathcal{R}e(\mathcal{C}_7\mathcal{C}_7'^*)}{|\mathcal{C}_7|^2+|\mathcal{C}_7'|^2}}$$

$$\boxed{A_\mathrm{T}^{\mathrm{Im}}(q^2\to 0) = \frac{2\mathcal{I}m(\mathcal{C}_7\mathcal{C}_7'^*)}{|\mathcal{C}_7|^2+|\mathcal{C}_7'|^2}}$$

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

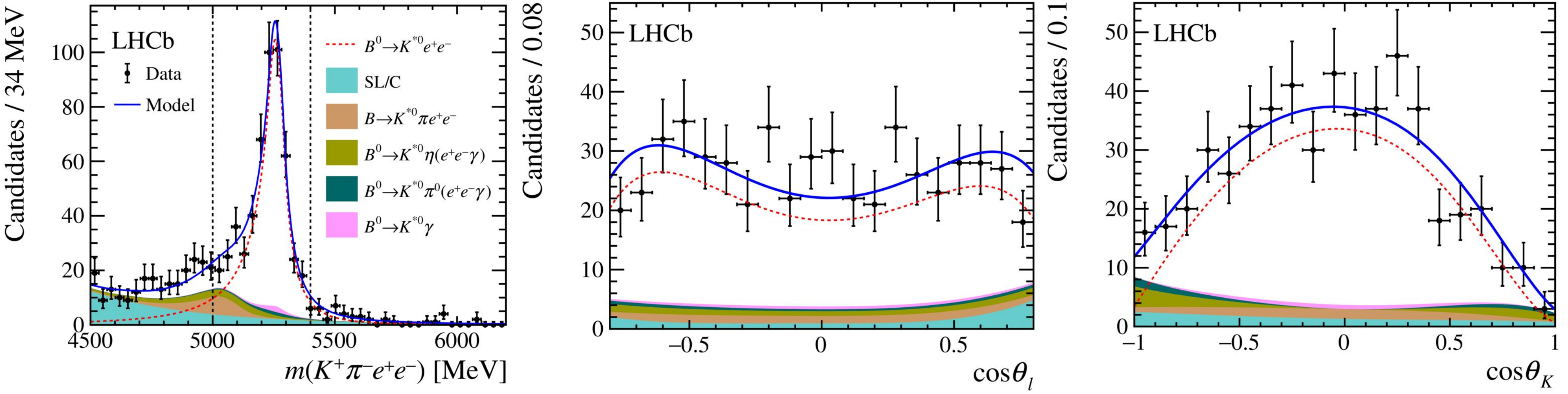
- Run 1 analysis: $q^2 \in [0.002, 1.120]$ GeV^2/c^4
- Run 1+2: $q^2 \in [0.0008, 0.257]$ GeV^2/c^4

Exploiting $b \longrightarrow s e^+ e^-$ at very low q^2

arXiv:2010.06011

NEW

Much cleaner selection achieved in new analysis



Mass shape, angular acceptance and model validated with $B \to K^* \gamma (\to e^+ e^-)$

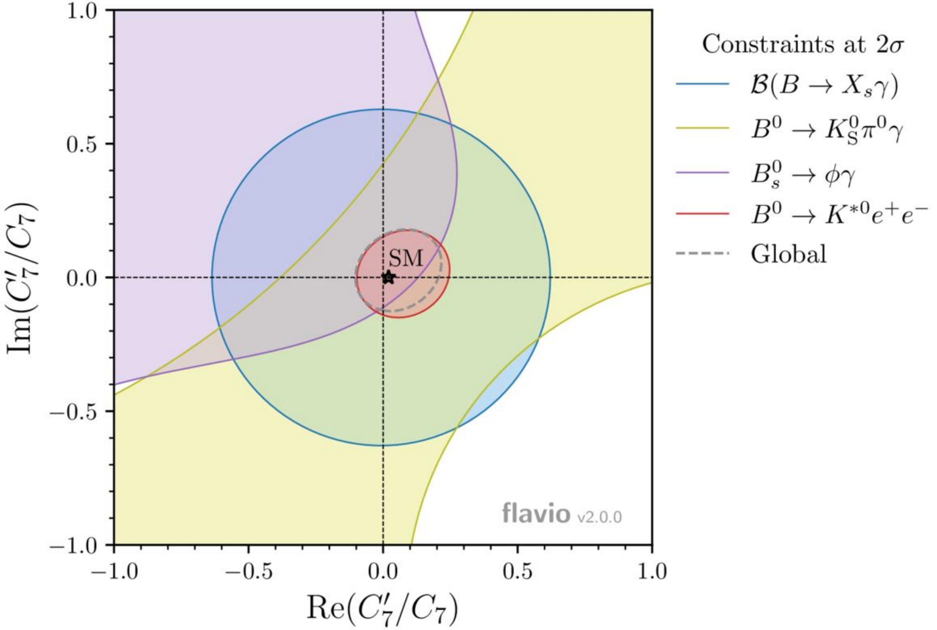
Exploiting b⟶se$^+$e$^-$ at very low q^2

arXiv:2010.06011

NEW

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

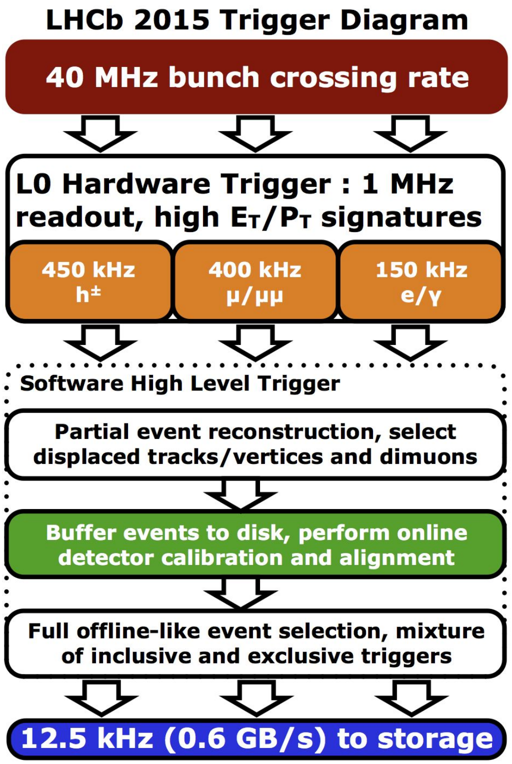
$$
\begin{aligned}
F_{\mathrm{L}} &= 0.044 \pm 0.026 \pm 0.014, \\
A_{\mathrm{T}}^{\mathrm{Re}} &= -0.06 \pm 0.08 \pm 0.02, \\
A_{\mathrm{T}}^{(2)} &= +0.11 \pm 0.10 \pm 0.02, \\
A_{\mathrm{T}}^{\mathrm{Im}} &= +0.02 \pm 0.10 \pm 0.01,
\end{aligned}
$$



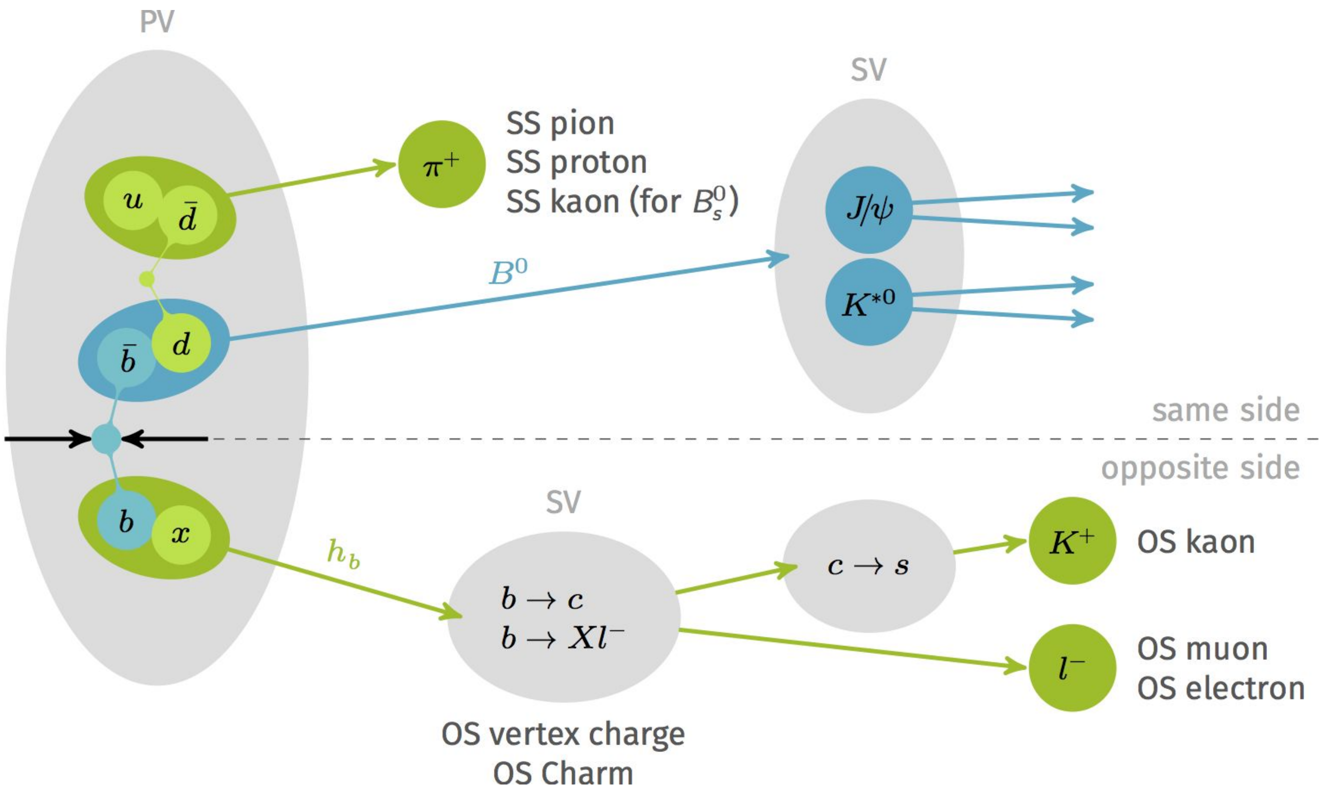
Perfect agreement with SM

still room for NP?

LHCb Trigger



Flavour tagging at LHCb



LHCb Upgrade for photon polarisation

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