Latest results with radiative decays and future prospects

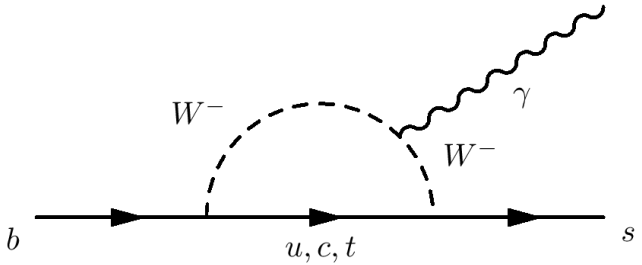
Towards the Ultimate Precision in Flavour Physics

03/04/19 IPPP/Durham

Carla Marin Benito

Radiative b-decays

b→ s(d)γ are Flavour-Changing-Neutral-Currents (FCNC) → crucial tests of the Standard Model (SM)

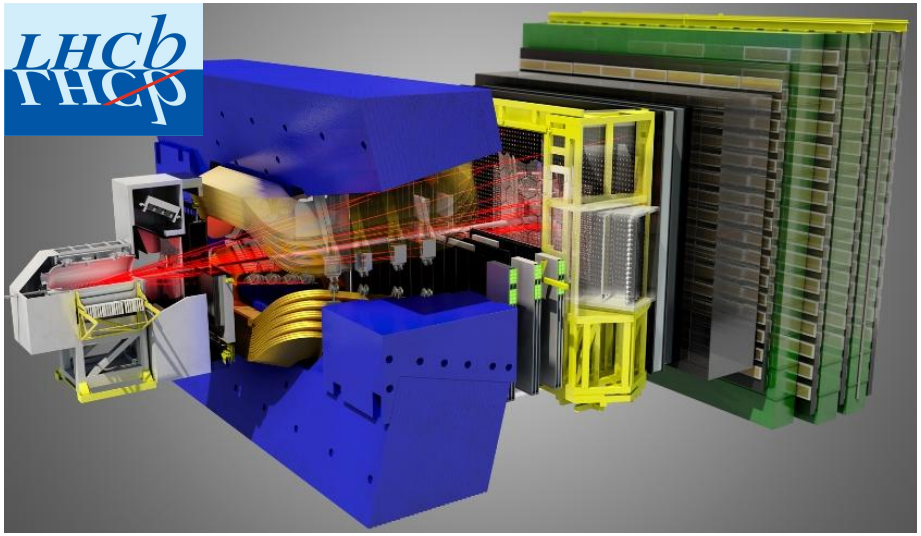


$$\mathcal{H}_{eff} \propto V_{ts}^* V_{tb} (C_7 O_7 + C'_7 O'_7)$$

- generated by O_7 at leading order (LO) in the SM, O'_7 suppressed by m_q/m_b
- C_7 strongly constrained by BR and direct CP measurements
- room for New Physics (NP) in C'_7 → photon polarisation

The major players

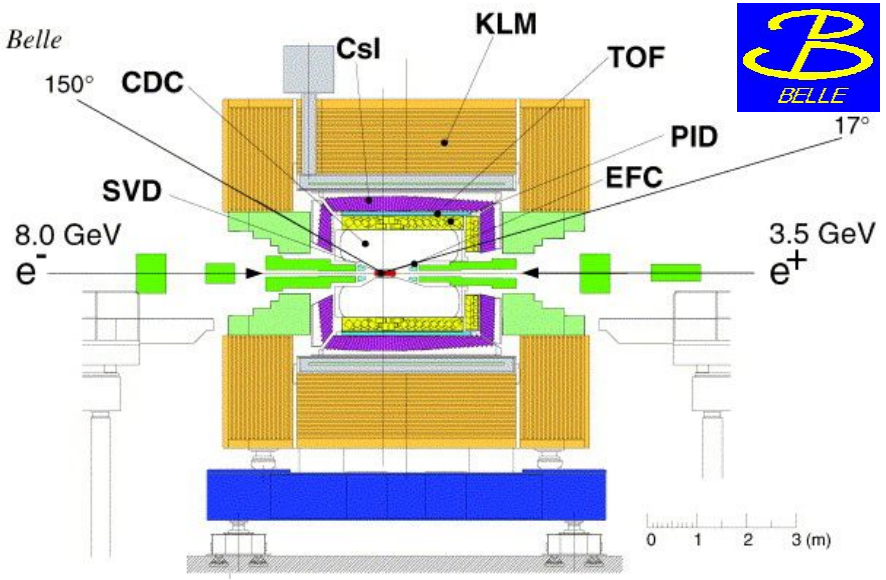
Many BaBar and Cleo contributions as well



JINST 3 (2008) S08005

- pp collisions: high background
- 7 fb^{-1} on tape: all b species
- forward spectrometer

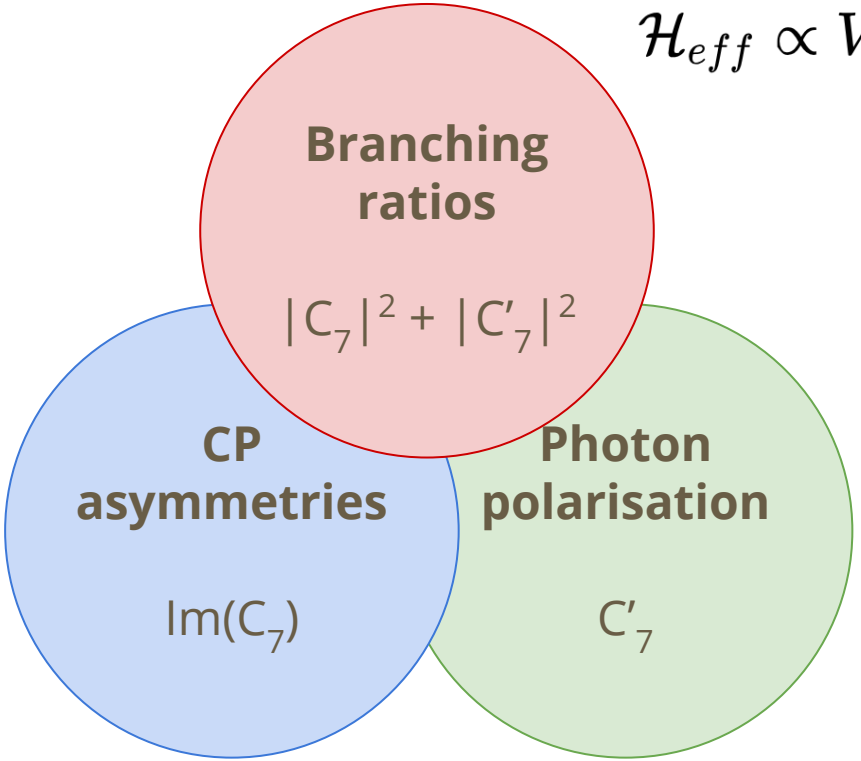
Nucl. Instrum. Methods Phys. Res., A 479, 117 (2002)



- e^+e^- collisions: very clean environment
- 1 ab^{-1} on tape: B^0 and B^+, some B_s as well
- hermetic detector, large coverage

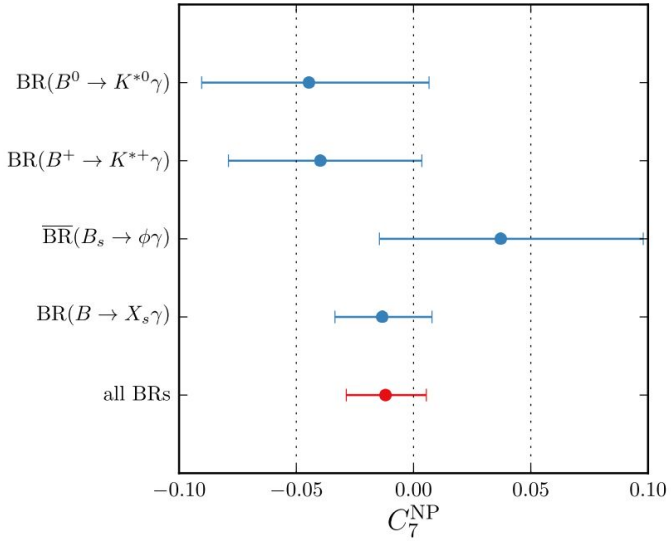
Radiative b-decay observables

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

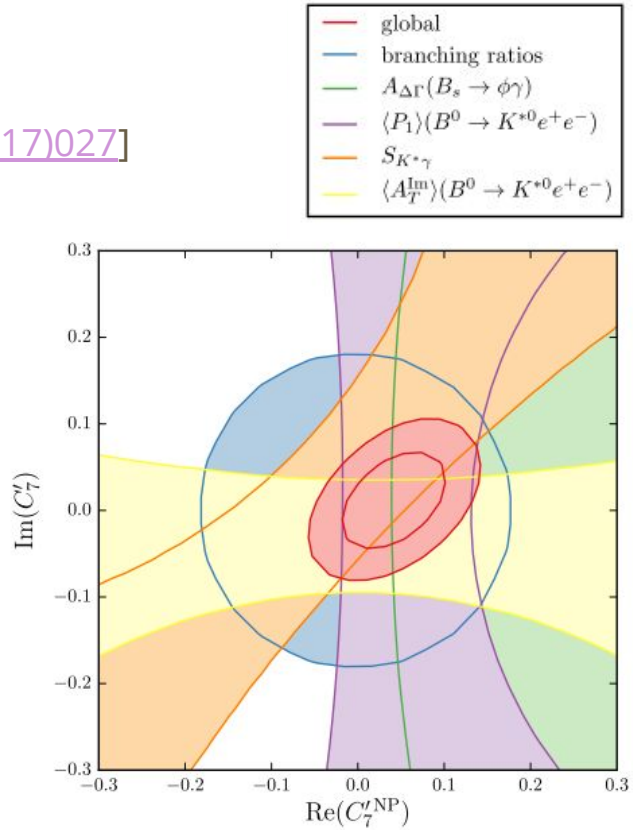


New Physics constraints

Paul & Straub [JHEP04(2017)027]



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

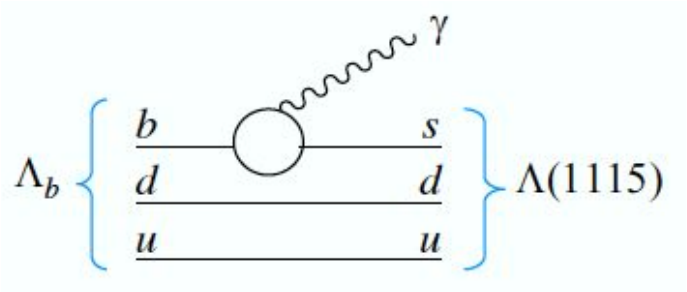


Latest results

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

LHCb-PAPER-2019-010

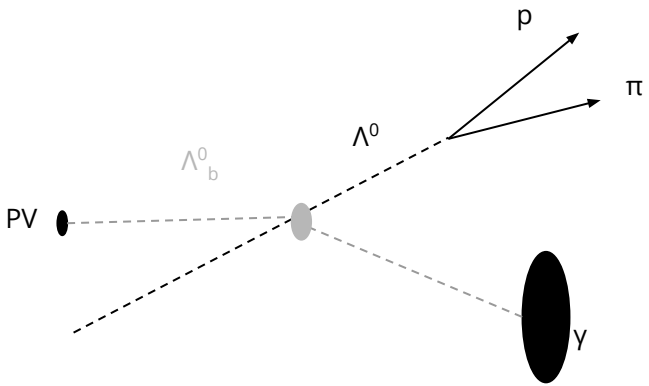
Baryonic b → sγ not observed
BR < $1.9 \cdot 10^{-3}$ [CDF PhysRevD.66.112002]



$BR_{SM} \in [0.06\text{-}1]\times10^{-5}$ [Wang et al., Mannel et al., Gan et al., Faustov et al.]

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

Very challenging reconstruction → dedicated reconstruction in Run 2



Huge combinatorial background mitigated with performant MVA

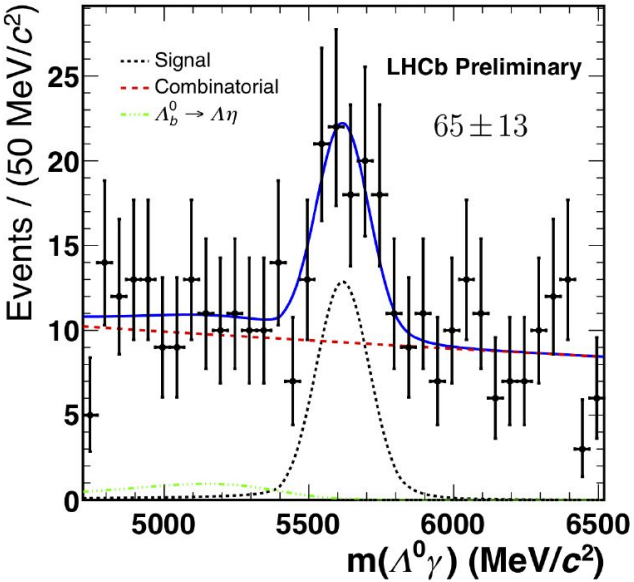
First observation of $\Lambda_b \to \Lambda^0\gamma$

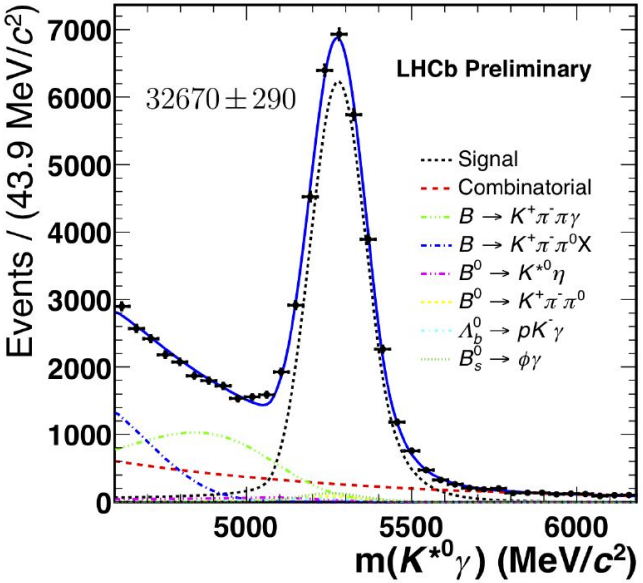
LHCb-PAPER-2019-010

LHCb 2016 data

Significance of 5.6σ
First observation!

Opens doors to photon polarisation measurement





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

Phys.Rev.D.99.032012

Isospin (Δ_{0-}) and CP (A_{CP}) asymmetry in $B \to X_s\gamma$

- BR($B \to X_s\gamma$) places strong constraints on NP models
  - $\sigma_{th} \sim \sigma_{exp} \sim 7\%$ but $\sigma_{\text{Belle II}} \sim 3\% \to$ theory improvement needed!
  - σ_{th} dominated by resolved photon contribution (RP): hard gluon - light quark scattering

$$\frac{\mathcal{B}^{78}_{\mathcal{RP}}}{\mathcal{B}} \simeq -\frac{(1\pm0.3)}{3}\Delta_{0-}$$

  - Recent evidence for isospin breaking in $B_d \to K^*\gamma$ [Belle Phys.Rev.Lett.119.191802]
  - if similar value for inclusive decay → sizeable RP; else → improvement on σ_{th}

- Direct CP asymmetry σ_{th} also dominated by RP → new observable:

$$\Delta A_{CP} = A_{CP}(B^+ \to X_s^+\gamma) - A_{CP}(B^0 \to X_s^0\gamma) \propto \widetilde{\Lambda}_{78} Im(\frac{C_8}{C_7})$$

Λ_{78} term from interference between C_7 and C_8 operators

Phys.Rev.D.99.032012

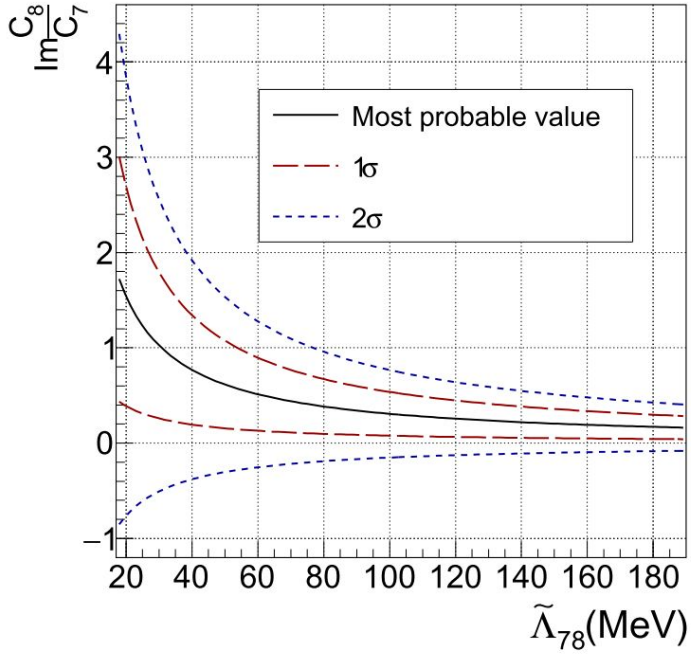
Isospin (Δ_{0-}) and CP (A_{CP}) asymmetry in $B \to X_s\gamma$

- Full Belle data
- Inclusive = sum of exclusive

$$\Delta_{0-} = [-0.48 \pm 1.49 \pm 0.97 \pm 1.15]\%$$

$$\frac{\mathcal{B}^{78}_{\rm RP}}{\mathcal{B}} \simeq (+0.16 \pm 0.50 \pm 0.32 \pm 0.38 \pm 0.05)\%$$

$$\Delta A_{CP} = [+3.69 \pm 2.65 \pm 0.76]\%$$



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

LHCb-PAPER-2019-015

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

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

$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.98^{+0.46\,+0.23}_{-0.52\,-0.20}$$

PRL 118(2017)2,021801

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

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

LHCb-PAPER-2019-015

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

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

$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.98^{+0.46\,+0.23}_{-0.52\,-0.20}$$

PRL 118(2017)2,021801

Require knowledge of the B_s flavour at production

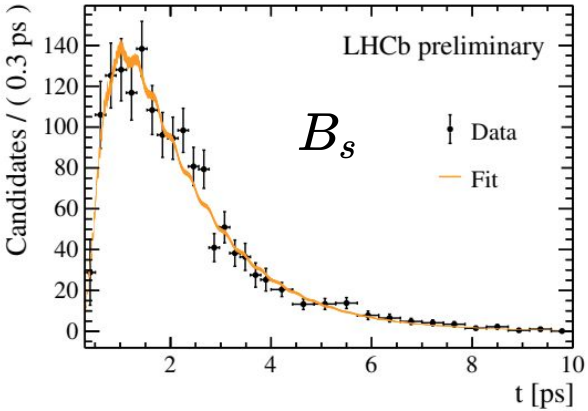
$$\mathcal{A}^{\Delta}_{\phi\gamma} \simeq \frac{\mathrm{Re}(e^{-i\phi_s} C_7\, C_7')}{|C_7|^2+|C_7'|^2} \qquad S_{\phi\gamma} \simeq \frac{\mathrm{Im}(e^{-i\phi_s} C_7\, C_7')}{|C_7|^2+|C_7'|^2}$$

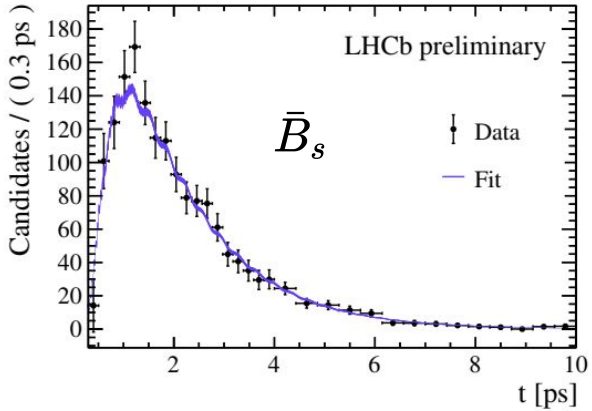
NEW from Moriond QCD!

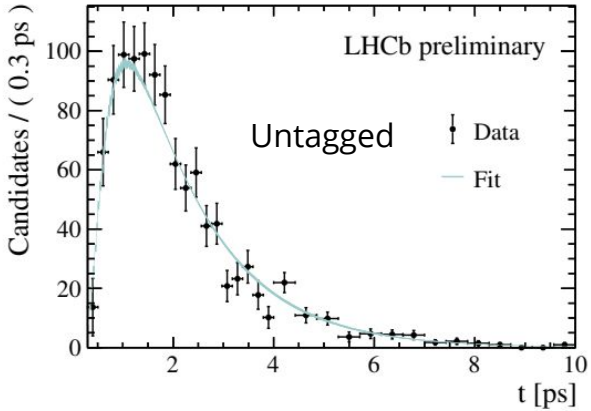
Photon polarization in $B_s \to \phi\gamma$

LHCb-PAPER-2019-015

- Simultaneous fit to $B_s \to \phi\gamma$ and control mode $B_d \to K^*\gamma$:





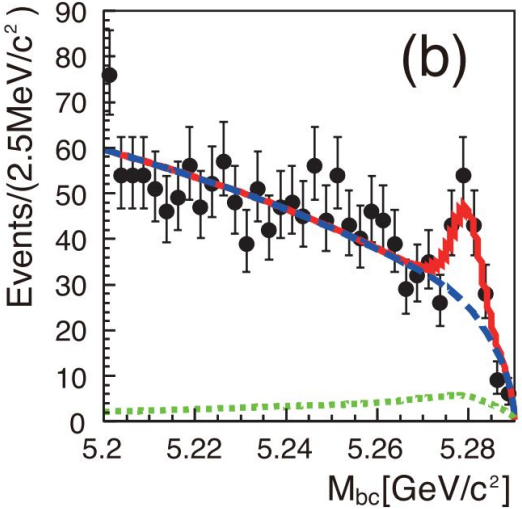


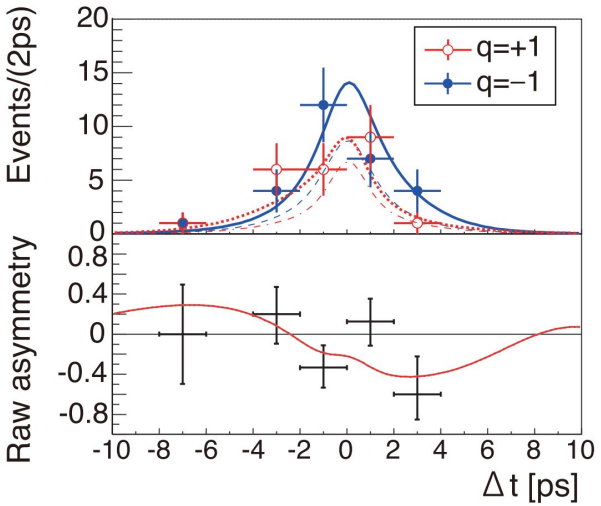
$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$

Photon polarization in $B^0 \to K_S \eta \gamma$

Phys.Rev.D.97.092003

- Full Belle data, $m(K_S \eta) < 2.1$ GeV/c^2, inclusive tagging





$$\mathcal{P}(\Delta t) \propto q\,[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)]$$

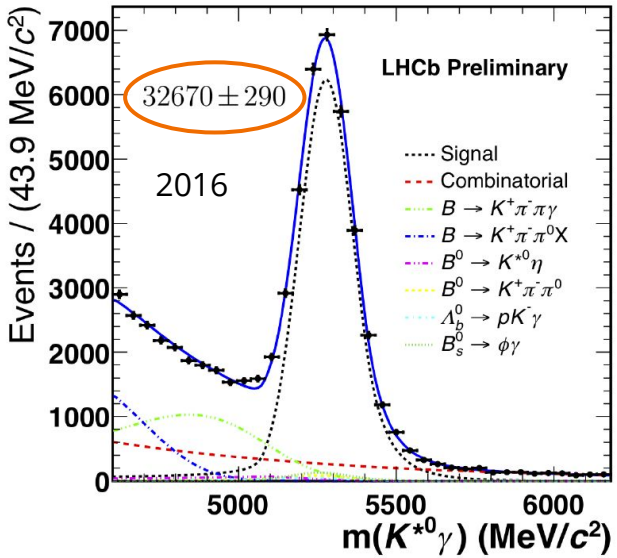
$$S_{K_S\eta\gamma} = -1.32 \pm 0.77 \pm 0.36$$
$$\mathcal{A}_{K_S\eta\gamma} = -0.48 \pm 0.41 \pm 0.07$$

Future prospects

+ upgrades

LHCb Run1+2: BR and asymmetries

BR($B_s \to \phi\gamma$) and $\Delta CP(B_d \to K^*\gamma)$



LHCb-PAPER-2019-010

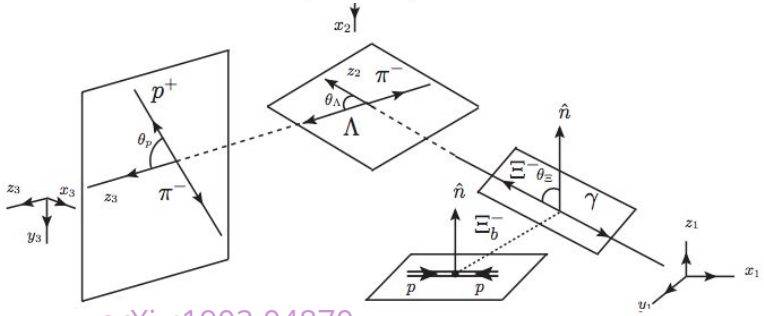
+ measure isospin asymmetry
+ explore higher Kπ and KK states

Explore more b-baryons

- $\Lambda_b \to \Lambda^*(pK)\gamma$
- $\Lambda_b \to N^*(p\pi)\gamma$
- $\Xi_b^- \to \Xi^-\gamma$ and $\Omega_b^- \to \Omega^-\gamma$

The latter give access to photon polarisation:

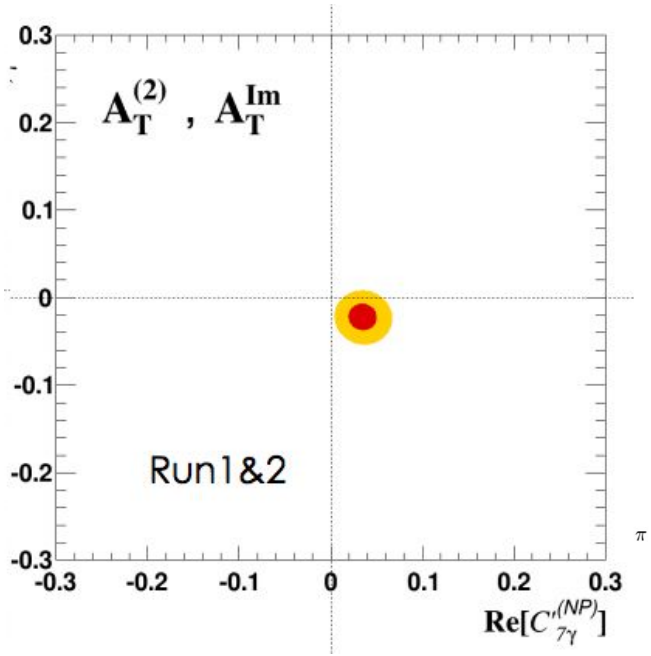
$$W(\theta_\Lambda, \theta_p) \propto 1 + \alpha_\Lambda \alpha_\Xi \cos\theta_p + \alpha_\gamma \alpha_\Xi \cos\theta_\Lambda + \alpha_\Lambda \alpha_\gamma \cos\theta_p \cos\theta_\Lambda .$$



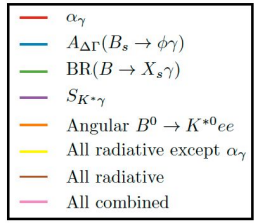
arXiv:1902.04870

See E. Kou's talk

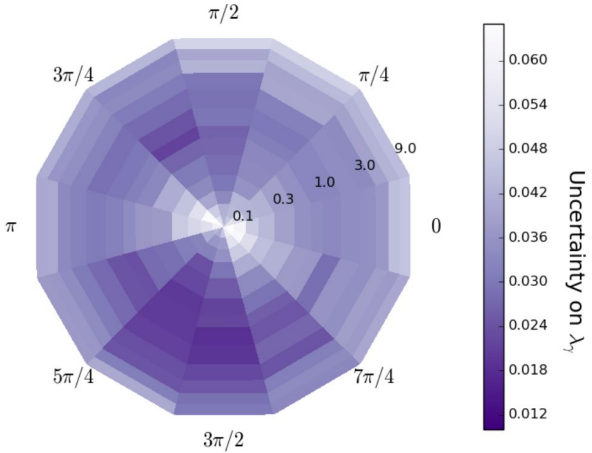
LHCb Run1+2: photon polarisation



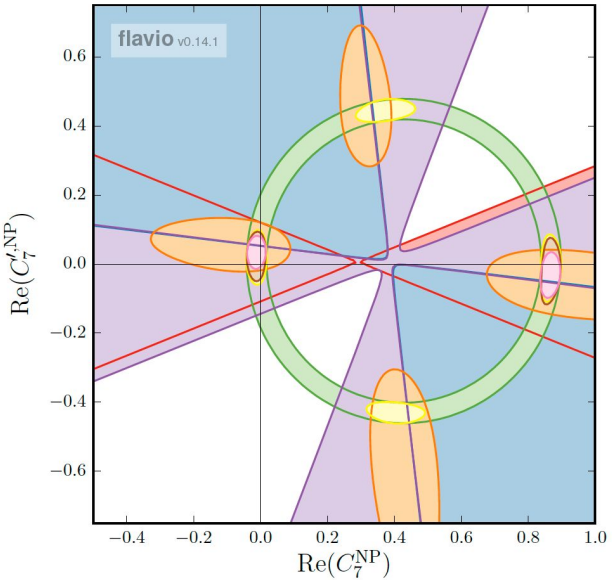
$B_d \to K^*ee$ CERN-THESIS-2015-219



$B \to K^+\pi^+\pi\gamma$ arXiv:1902.09201



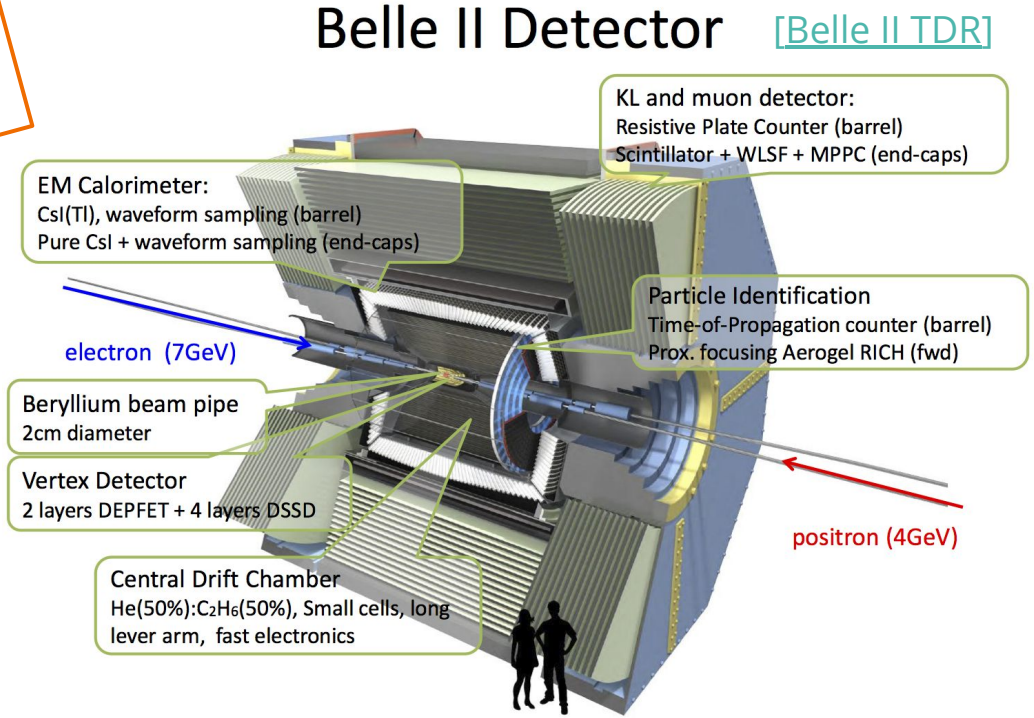
$\sigma^{LHCb,9fb} \sim 0.009$, $\sigma^{BelleII,5ab} \sim 0.018$



$\Lambda_b \to \Lambda^0\gamma$ using Flavio
See also arXiv:1902.04870

The new signing

Taking physics data since last week!



See P. Urquijo's talk

Belle II: inclusive $B \to X_{s,d}\gamma$

Belle II Physics Book

Work on systematics is crucial!

Fully inclusive:

- photon E_T > 1.6 GeV possible
- better control of neutral hadron background needed

Sum of exclusive:

- add new modes with more stats

Observables	Belle 0.71 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B \to X_s\gamma)^{\text{lep-tag}}_{\text{inc}}$	5.3%	3.2%
$\mathrm{Br}(B \to X_s\gamma)^{\text{had-tag}}_{\text{inc}}$	13%	4.2%
$\mathrm{Br}(B \to X_s\gamma)_{\text{sum-of-ex}}$	10.5%	5.7%
$\Delta_{0+}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.1%	0.63%
$\Delta_{0+}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	9.0%	0.85%
$A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	1.3%	0.19%
$A_{CP}(B^0 \to X^0_s\gamma)_{\text{sum-of-ex}}$	1.8%	0.26%
$A_{CP}(B^+ \to X^+_s\gamma)_{\text{sum-of-ex}}$	1.8%	0.25%
$A_{CP}(B \to X_{s+d}\gamma)^{\text{lep-tag}}_{\text{inc}}$	4.0%	0.48%
$A_{CP}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	8.0%	0.70%
$\Delta A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.5%	0.30%
$\Delta A_{CP}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	16%	1.3%
$\mathrm{Br}(B \to X_d\gamma)_{\text{sum-of-ex}}$	30%	14%
$\Delta_{0+}(B \to X_d\gamma)_{\text{sum-of-ex}}$	30%	3.6%
$A_{CP}(B^+ \to X^+_{u\bar{d}}\gamma)_{\text{sum-of-ex}}$	42%	5.1%
$A_{CP}(B^0 \to X^0_{d\bar{d}}\gamma)_{\text{sum-of-ex}}$	84%	10%
$A_{CP}(B \to X_d\gamma)_{\text{sum-of-ex}}$	38%	4.6%
$\Delta A_{CP}(B \to X_d\gamma)_{\text{sum-of-ex}}$	93%	11%

Belle II: exclusive decays

Statistically dominated

Also double-radiative decays:

Observables	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B_d \to \gamma\gamma)$	30%	9.6%
$A_{CP}(B_d \to \gamma\gamma)$	78%	25%
$\mathrm{Br}(B_s \to \gamma\gamma)$	23%	–

WARNING: LHCb can also contribute to this mode! See LHCb-PUB-2018-006

Belle II Physics Book

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	(Belle II $50\,\mathrm{ab}^{-1}$
$\Delta_{0+}(B \to K^*\gamma)$	2.0%	0.53%
$A_{CP}(B^0 \to K^{*0}\gamma)$	1.7%	0.21%
$A_{CP}(B^+ \to K^{*+}\gamma)$	2.4%	0.29%
$\Delta A_{CP}(B \to K^*\gamma)$	2.9%	0.36%
$S_{K^{*0}\gamma}$	0.29	0.030
$\mathrm{Br}(B^0 \to \rho^0\gamma)$	24%	4.5%
$\mathrm{Br}(B^+ \to \rho^+\gamma)$	30%	5.0%
$\mathrm{Br}(B^0 \to \omega\gamma)$	50%	5.8%
$\Delta_{0+}(B \to \rho\gamma)$	18%	1.9%
$A_{CP}(B^0 \to \rho^0\gamma)$	44%	3.8%
$A_{CP}(B^+ \to \rho^+\gamma)$	30%	3.0%
$A_{CP}(B^0 \to \omega\gamma)$	91%	7.7%
$\Delta A_{CP}(B \to \rho\gamma)$	53%	4.8%
$S_{\rho^0\gamma}$	0.63	0.064
$\lvert V_{td}/V_{ts}\rvert_{\rho/K^*}$	12%	7.6%
$\mathrm{Br}(B_s^0 \to \phi\gamma)$	23%	–
$\mathrm{Br}(B^0 \to K^{*0}\gamma)/\mathrm{Br}(B_s^0 \to \phi\gamma)$	23%	–
$\mathrm{Br}(B_s^0 \to K^{*0}\gamma)$	–	–
$A_{CP}(B_s^0 \to K^{*0}\gamma)$	–	–
$\mathrm{Br}(B_s^0 \to K^{*0}\gamma)/\mathrm{Br}(B_s^0 \to \phi\gamma)$	–	–
$\mathrm{Br}(B^0 \to K^{*0}\gamma)/\mathrm{Br}(B_s^0 \to K^{*0}\gamma)$	–	–

LHCb Upgrade II (see V. Gligorov and C. Langenbruch talks)

LHCb Upgrade II physics case

LHCb	300 fb^{-1}	
	Yield	$\sigma_{stat}(\gamma_{pol})$
$B_s \to \phi\gamma$	800k	0.02
$B^0 \to K_S\pi^+\pi^-\gamma$	200k	
$B^+ \to K^+\pi^+\pi^-\gamma$	2M	< 1%
$B^0 \to K^*e^+e^-$	20k	2%
$\Lambda_b \to \Lambda^0\gamma$	10k	4%

Improvements in systematics needed but feasible:

- π^0 backgrounds
- angular background distributions
- detector asymmetries
- external inputs: BR, hadronisation

Summary

- Radiative b-decays provide important tests of the SM
  - NP very constrained already in C_7 but still room in C'_7

- Active field with fresh LHCb and Belle results:
  - first radiative b-baryon decay observed!
  - new modes & techniques for photon polarisation measurements

- Much more to come soon:
  - LHCb full Run 2 analyses
  - Belle II

} mostly statistically dominated, work on systematics needed for inclusive measurements

Summary

- Radiative b-decays provide important tests of the SM
  - NP very constrained already in $C_{7,9,10}$ but still room in $C'_{7,9,10}$
- Active field wit
  - first radiative
  - new modes &

- Much more to come soon:
  - LHCb full Run 2 analyses
  - Belle II

} mostly statistically dominated, work on systematics needed for inclusive measurements

BACK-UP

Search for $B^+ \to \ell\nu\gamma$ at Belle

Phys.Rev. D98 (2018) 11 112016
from M. Prim's talk at Moriond EW

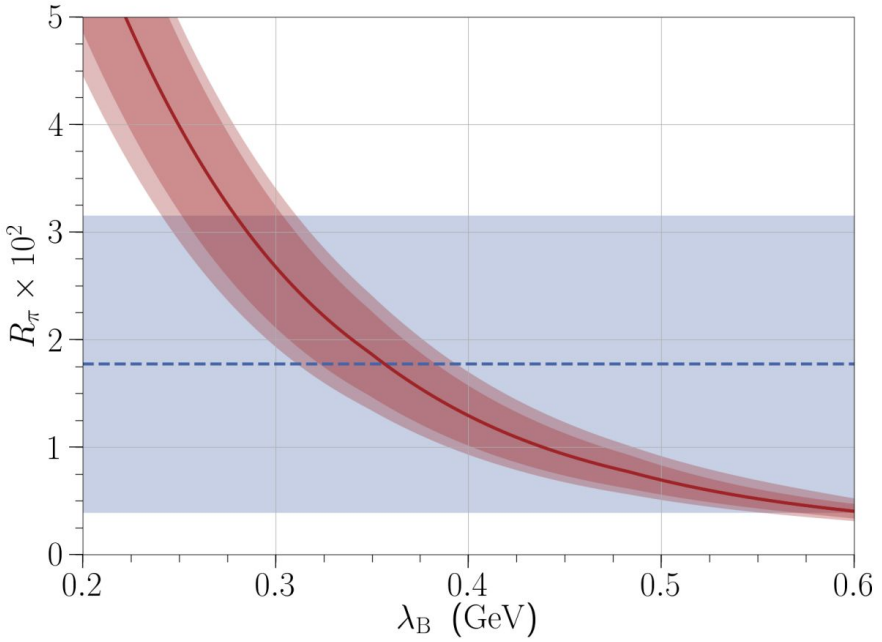
$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha_{em} G_F^2 m_B^4 |V_{ub}|^2}{48\pi^2} x_\gamma^3 (1 - x_\gamma)[F_A^2 + F_V^2]$$

$$R_\pi = \frac{\Delta\mathcal{B}(B^+ \to \ell^+ \nu_\ell \gamma)}{\mathcal{B}(B^+ \to \pi^0 \ell^+ \nu_\ell)} = \frac{\Delta\Gamma(\lambda_B)}{\Gamma(B^+ \to \pi^0 \ell^+ \nu_\ell)}$$

R_π removes dependence of V_{ub}.

$$R_\pi^{\text{measured}} = (1.7 \pm 1.4) \times 10^{-2}$$

based on theoretical input from:
Beneke et al., JHEP 07:154 (2018)
HFLAV, Eur. Phys. J., C77:895, (2017)



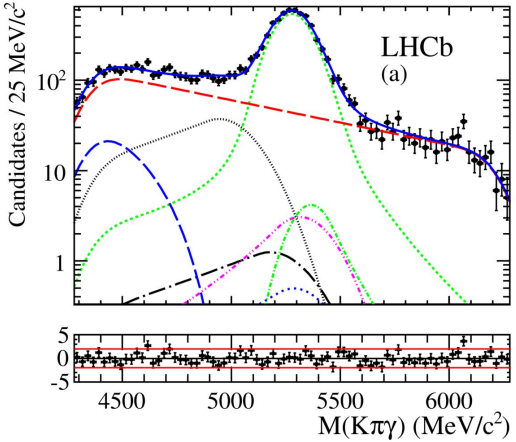
$\lambda_B > 0.24$ GeV @ 90% C.L.[a]

a: Phys.Rev. D98 (2018) no.11, 112016

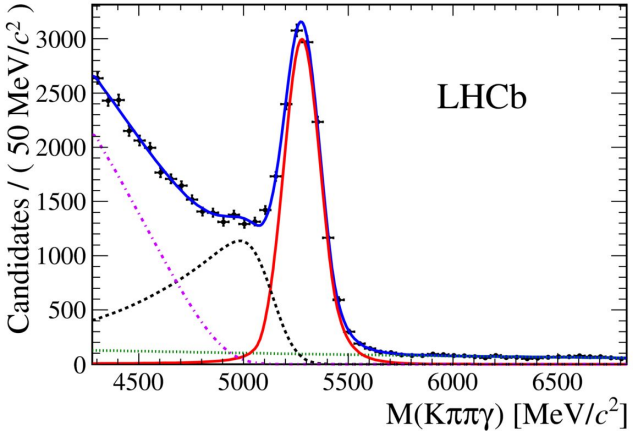
Radiative b-decays at LHCb

Main challenges:

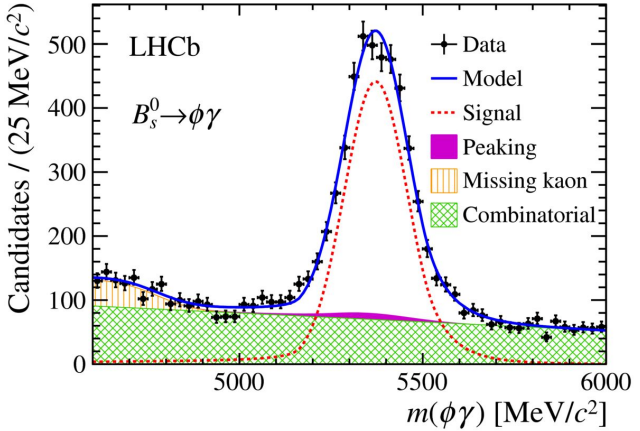
- mass resolution: ~100 MeV (~22 MeV for B → hh)
- partial and mis-id backgrounds (bkg): π^0/γ separation



[Nucl. Phys. B867 (2013)]



[Phys. Rev. Lett. 112, 161801 (2014)]



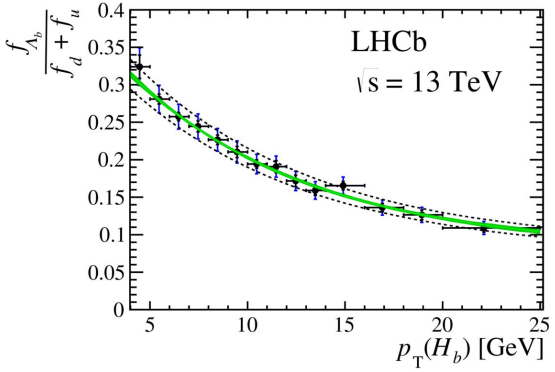
[Phys. Rev. Lett. 118, 021801 (2017)]

b-baryon decays

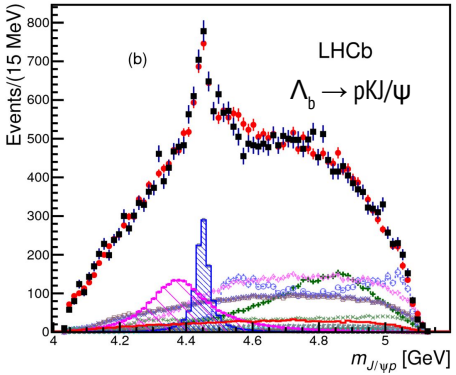
Offer complementary observables to probe the SM:

- two spectator quarks → different Form Factors
- half-integer spin → richer angular distributions

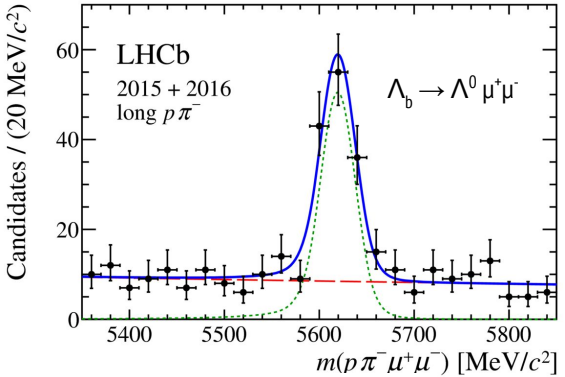
Largely unexplored so far, LHCb can exploit large production at LHC:



[arXiv:1902.06794]



[Phys. Rev. Lett. 115, 072001]



[JHEP 09 (2018) 146]

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

[Legger and Schietinger]

Most interesting observable is the photon polarisation:

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

at LO in the SM:

$$\alpha_\gamma^{LO} = \frac{1-|r|^2}{1+|r|^2} \qquad r = \frac{C'_7}{C_7} \sim \frac{m_s}{m_b}$$

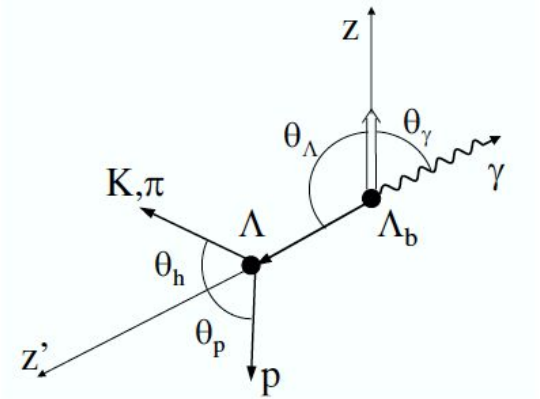
Accessible in $\Lambda_b \to \Lambda^0\gamma$ through angular analysis:

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

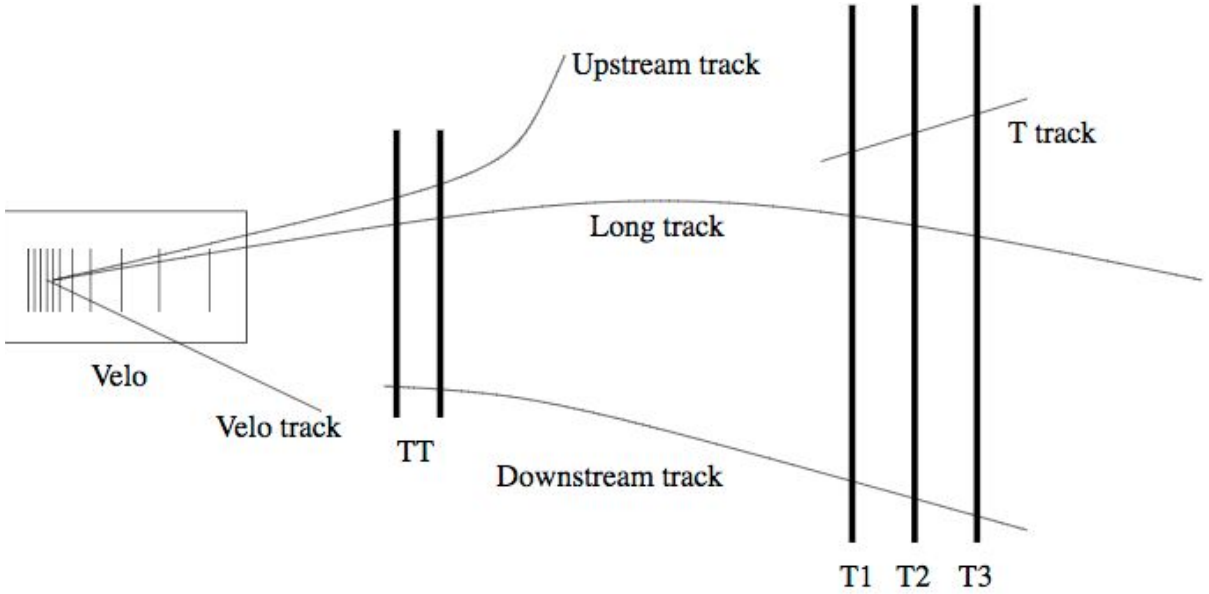
$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_{p,1/2} \cos\theta_p$$

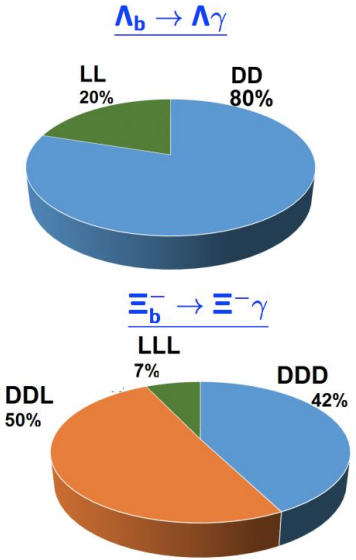
$P_{\Lambda b}$ = (0.06 ± 0.07) [Phys. Lett. B 724 (2013) 27]

$\alpha_{p,½}$ = (0.642 ± 0.013) [PDG]



Track types at LHCb





Systematics

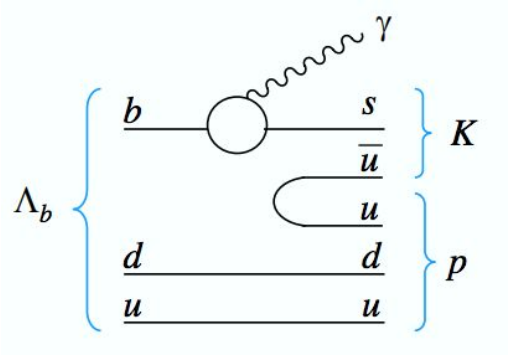
[LHCb-ANA-2018-033]

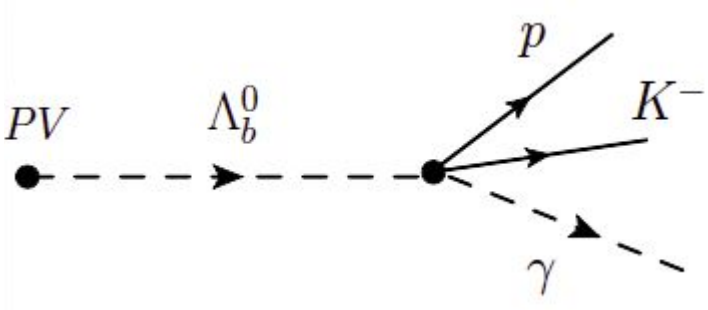
Source	Value (%)
$B^0 \to K^{*0}\gamma$ backgrounds	2.65
Fit model	X
$f_{\Lambda_b^0}/f_{B^0}$	8.7
Input branching fractions	3.0
Limited MC statistics	1.7
Efficiency ratio	0.72
MC/Data	X
Total	X

affects signal significance

$\Lambda_b \rightarrow \Lambda^* \gamma$

Same b→sγ transition with contributions from heavier Λ* resonances





- experimentally more accessible: Λ*→pK strongly
  - prompt decay inside vertex detector
  - Λ_b vtx can be reconstructed

Photon polarisation in $\Lambda_b \to pK\gamma$

[Legger and Schietinger]

- J = 1/2 → angular distributions as for Λ^0

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

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

in this case:

- $\alpha_{p,½} = 0$ (strong decay)
- $P_{\Lambda b}$ = (0.06 ± 0.07) at LHC
  [Phys. Lett. B 724 (2013) 27]

- J = 3/2

$$\frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_{\gamma,\frac{3}{2}} P_{\Lambda_b} \cos\theta_\gamma$$

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_{p,\frac{3}{2}} \cos^2\theta_p$$

with:

$$\alpha_\gamma = \frac{1}{2}\,\alpha_{\gamma,\frac{3}{2}} \left(1 - \frac{3}{\alpha_{p,\frac{3}{2}}}\right)$$

sensitivity to α_γ suppressed by initial Λ_b polarisation

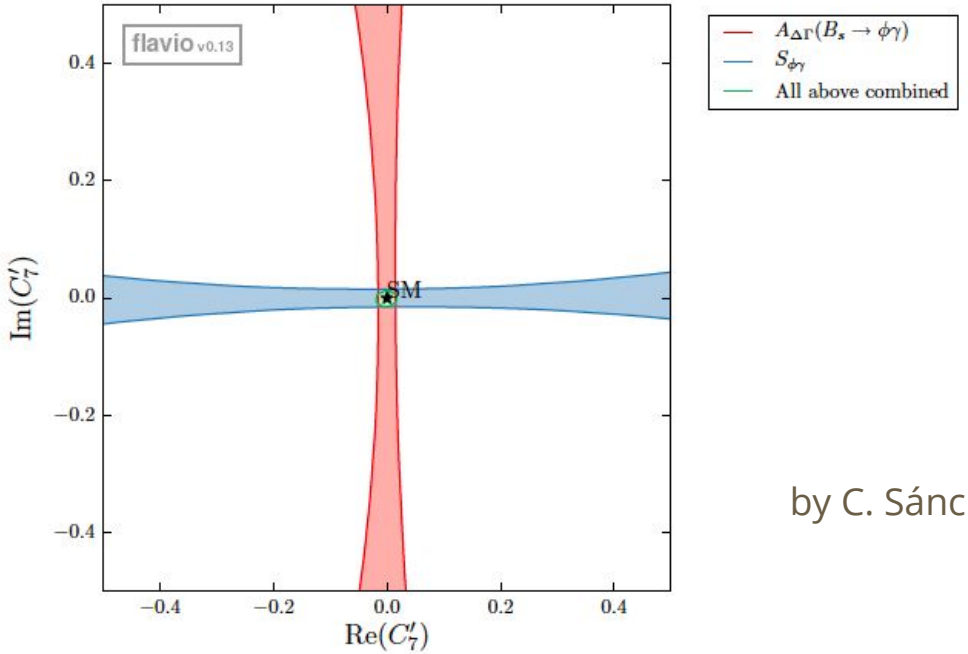
*for J > 3/2, more helicity amplitudes than observables

Belle sum of exclusive

Mode ID	Final state	Mode ID	Final state
1	$K^+\pi^-$	20	$K^0_S\pi^+\pi^0\pi^0$
2	$K^0_S\pi^+$	21	$K^+\pi^+\pi^-\pi^0\pi^0$
3	$K^+\pi^0$	22*	$K^0_S\pi^+\pi^-\pi^0\pi^0$
4*	$K^0_S\pi^0$	23	$K^+\eta$
5	$K^+\pi^+\pi^-$	24*	$K^0_S\eta$
6*	$K^0_S\pi^+\pi^-$	25	$K^+\eta\pi^-$
7	$K^+\pi^-\pi^0$	26	$K^0_S\eta\pi^+$
8	$K^0_S\pi^+\pi^0$	27	$K^+\eta\pi^0$
9	$K^+\pi^+\pi^-\pi^-$	28*	$K^0_S\eta\pi^0$
10	$K^0_S\pi^+\pi^+\pi^-$	29	$K^+\eta\pi^+\pi^-$
11	$K^+\pi^+\pi^-\pi^0$	30*	$K^0_S\eta\pi^+\pi^-$
12*	$K^0_S\pi^+\pi^-\pi^0$	31	$K^+\eta\pi^-\pi^0$
13	$K^+\pi^+\pi^+\pi^-\pi^-$	32	$K^0_S\eta\pi^+\pi^0$
14*	$K^0_S\pi^+\pi^+\pi^-\pi^-$	33	$K^+K^+K^-$
15	$K^+\pi^+\pi^-\pi^-\pi^0$	34*	$K^+K^-K^0_S$
16	$K^0_S\pi^+\pi^+\pi^-\pi^0$	35	$K^+K^+K^-\pi^-$
17	$K^+\pi^0\pi^0$	36	$K^+K^-K^0_S\pi^+$
18*	$K^0_S\pi^0\pi^0$	37	$K^+K^+K^-\pi^0$
19	$K^+\pi^-\pi^0\pi^0$	38*	$K^+K^-K^0_S\pi^0$

LHCb Upgrade for photon polarisation

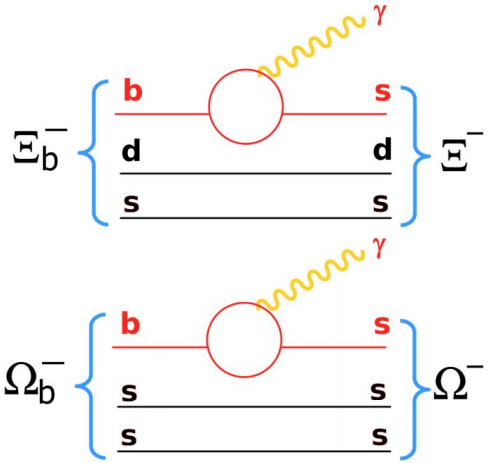
An example with 300 fb^{-1} → $\sigma(A^{\Delta}) \sim \sigma(S) \sim 0.05$

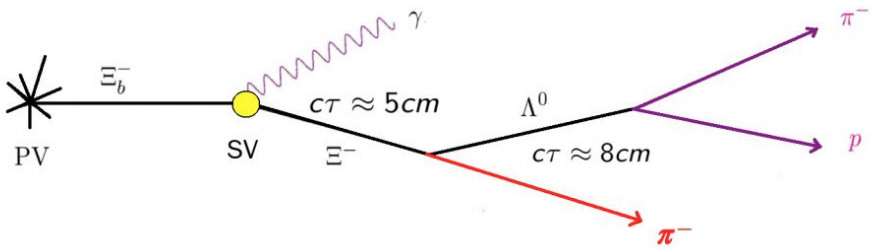


by C. Sánchez Mayordomo

$\Xi_b^- \to \Xi^- \gamma$ and $\Omega_b^- \to \Omega^- \gamma$

Baryon b → sγ transitions with different spectator quarks





- More complex decay topology → very challenging reconstruction
  - most decays outside LHCb vertex locator
  - cannot reconstruct Ξ_b^- decay vertex