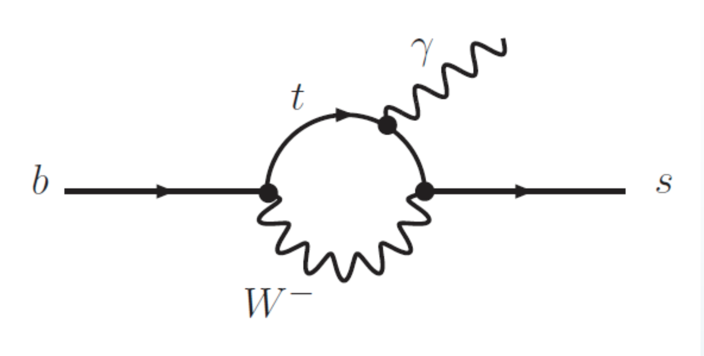

Rare and radiative B decays at LHCb

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On behalf of the LHCb collaboration

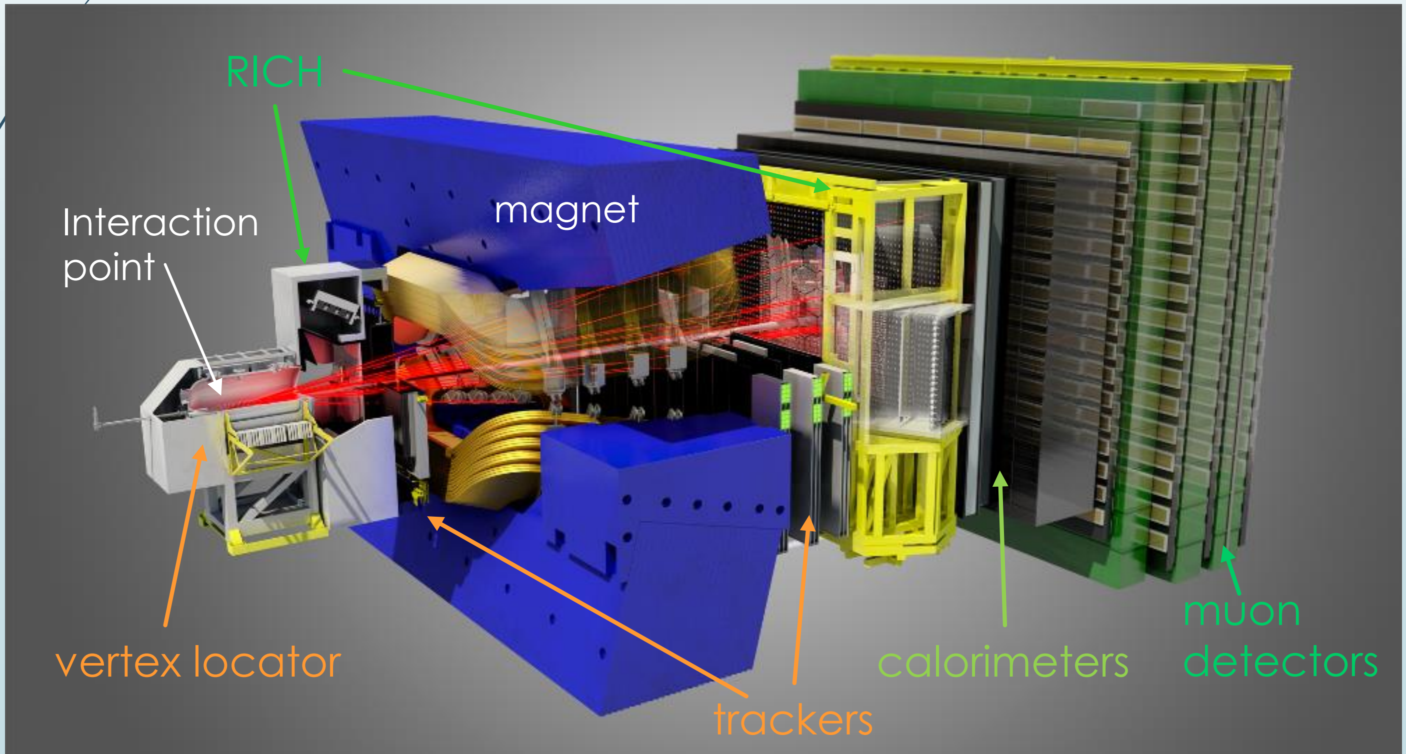
PHOTON 2019

3-7 June, INFN – LFN, Frascati

INT. J. MOD. PHYS. A 30, 1530022 (2015)

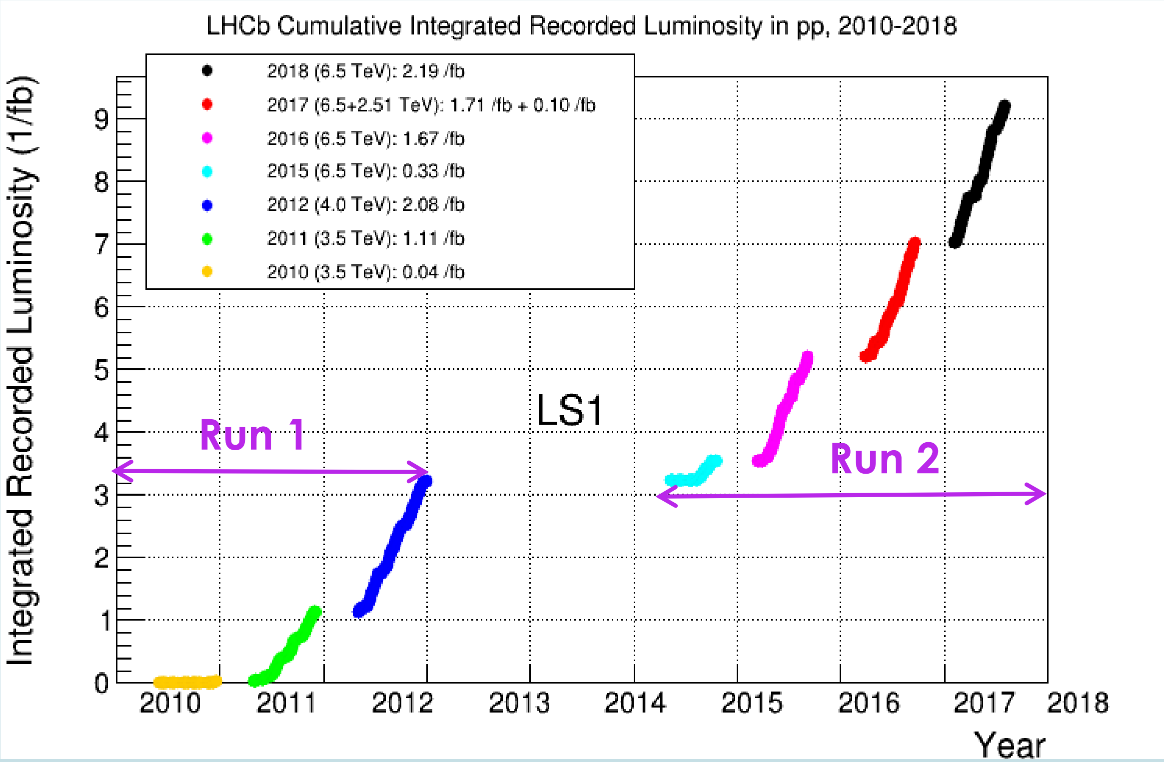
The LHCb detector

- Forward arm spectrometer to study b- and c-hadron decays (2<η<5).
  - Good vertex and impact parameter resolution ($\sigma(IP) = 15 + 29/p_T\ \mu m$).
  - Excellent momentum resolution ($\sigma(mB) \sim 25\ MeV/c^2$ for 2-body decays).
  - Excellent particle identification (μ ID 97% for ($\pi \rightarrow \mu$) misID of 1-3%).
  - Versatile and efficient trigger.



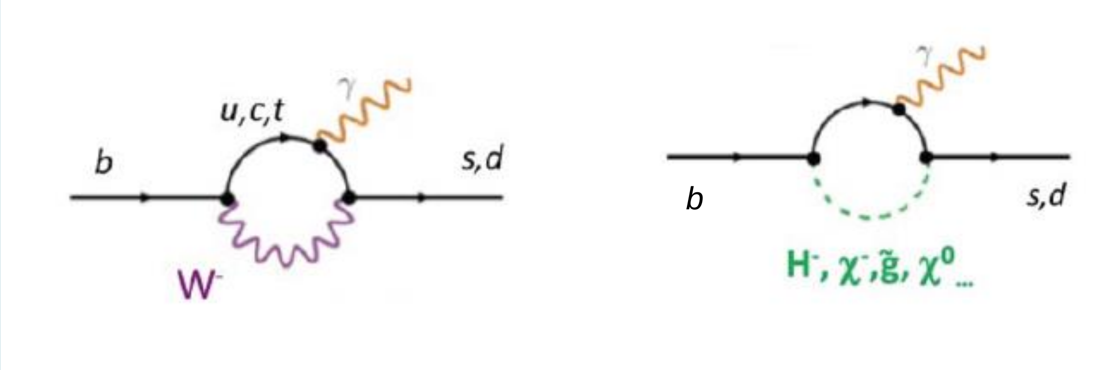
LHCb dataset

- **Run 1** (2010-2012): 7/8 TeV pp collisions; $\int \mathcal{L} = 3\ fb^{-1}$
- **Run 2** (2015-2018): 13 TeV pp collisions; $\int \mathcal{L} = 6\ fb^{-1}$
  - Production rates a factor 2 larger → x 4 larger yields.



Introduction to radiative B decays

- Radiative b-hadron decays correspond to $b \rightarrow q\gamma$ $(q = d, s)$ transitions.
- These Flavour-Changing Neutral Current (FCNC) transitions are forbidden at tree level in the Standard Model (SM).
  - Branching fractions, BR < 10^{-4}.
- Sensitive probes of New Physics (NP) through the study of branching fractions, angular observables, CP asymmetries and measurements of the polarisation of the photon emitted in the decay.
  - Indirect searches can probe NP at larger energy scales.

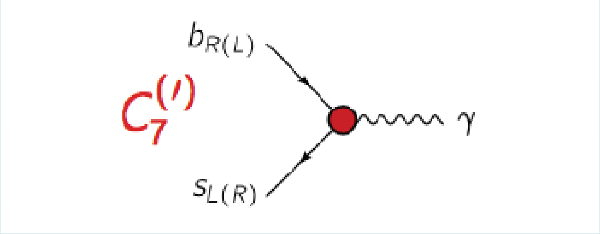


- FCNC are described by an effective Hamiltonian in the form of an Operator Product Expansion, which allows to identify the types of operators (O_i) that enter in each transition, along with their corresponding Wilson coefficients (C_i).

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i \{C_i O_i + \underbrace{C_i' O_i'}_{\text{Right-handed part (supressed in SM)}}\} + \sum_i \frac{C_i^{NP}}{\Lambda^2} O_i^{NP}$$

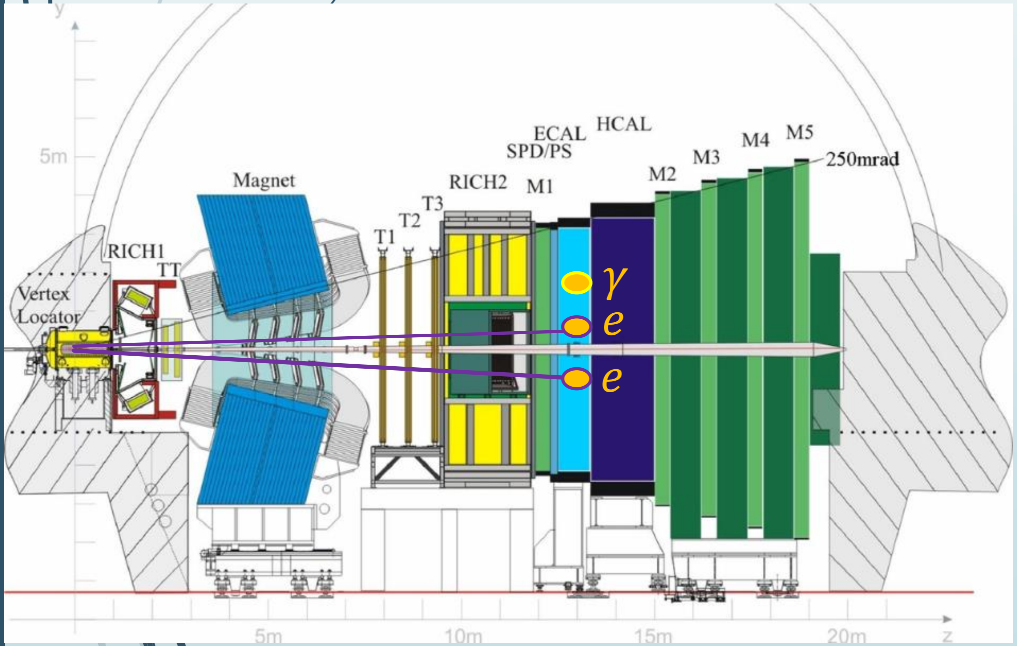
i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

- Leading operator for radiative decays is the electromagnetic operator O_7.
- Look for deviations of the values of the Wilson coefficients with respect to the SM predictions as a sign of NP.



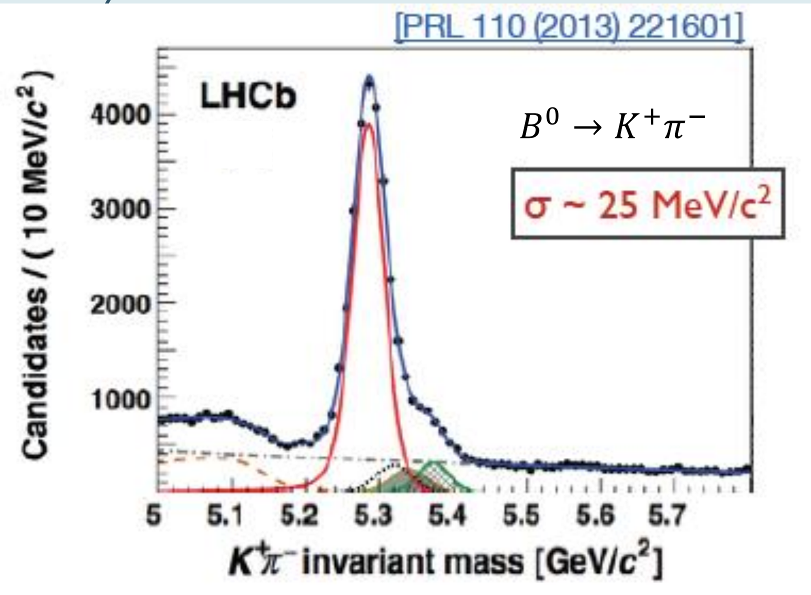
Photon reconstruction

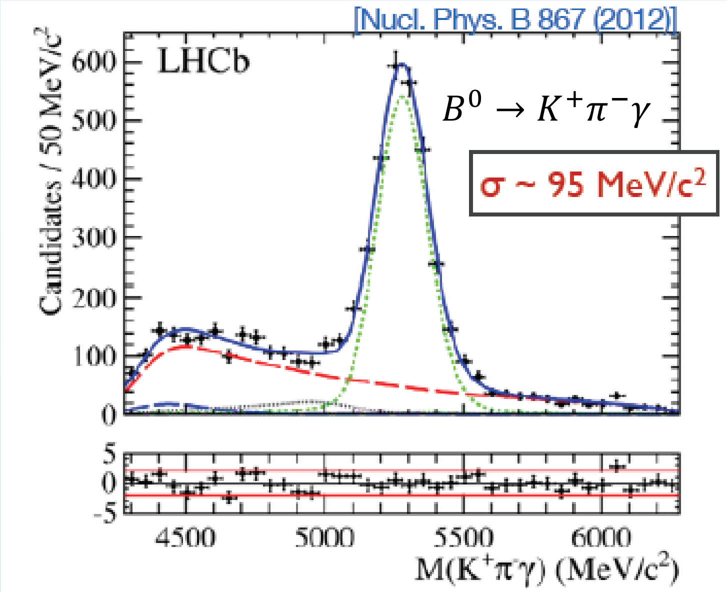
- Photons are mainly reconstructed from energy deposits in the Electromagnetic Calorimeter (of Shashlik type).
  - Or as converted photons $\gamma \to e^+e^-$ with the tracking system. Better mass resolution (around factor 3), but much lower efficiency than calorimetric photons (around factor 15 in yield).



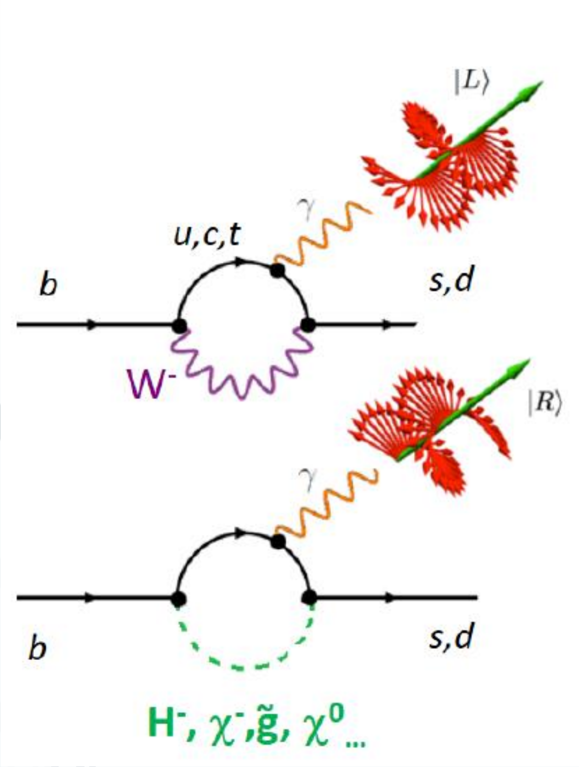
- Due to trigger constraints and large combinatorics the radiative decays mostly rely on high p_T photons.
  - E_T>2.5 or 3 GeV;
  - Efficiency~30-40% (vs 80-90% dimuon channels).

- Decays with photons in the final state are more challenging due to:
  - no constraint on vertexing from γ,
  - large photon multiplicity and
  - limited mass resolution (dominated by the photon reconstruction).
- Radiative reconstruction rates in Run-1:
  - $B^0 \to K^{*0}\gamma$: ~10000 candidates/fb^{-1}
  - $B_s^0 \to \phi\gamma$: ~1500 candidates/fb^{-1}





Photon polarisation



- Due to the chiral structure of the W boson, in SM the photon polarisation is predominantly left-handed.
  - Amplitude suppressed by m_q/m_W with m_q the mass of the right-handed quark.

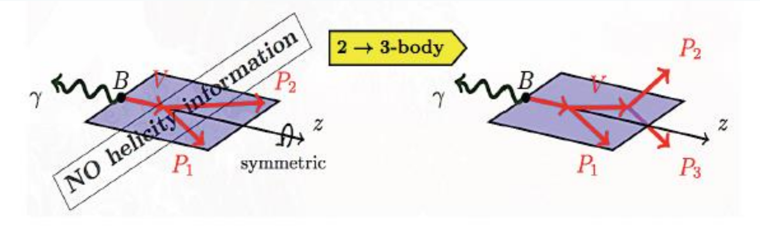
$$\frac{C_7'}{C_7} = \frac{A_R(b_L \to s_R \gamma_R)}{A_L(b_R \to s_L \gamma_L)} \approx \frac{m_s}{m_b} = 0.02$$

[Descotes-Genon et al., JHEP 06 (2011) 099]

- Right-handed component could be enhanced in NP models.
  - For instance, $\left|\frac{A_R}{A_L}\right|$ up to 0.5 in LRSM.

[Atwood et al., PRL 79 (1997) 185-188]
[Yu et al., JHEP 12 (2013) 102]

- Experimentally, the photon polarisation can be extracted from:
  - Angular distribution of radiative decays with 3 charged final state particles, e.g.
    - $B^+ \to K^+\pi^+\pi^-\gamma$ Phys. Rev. Lett. 112 (2014) 161801 ← First observation that the photon is polarised

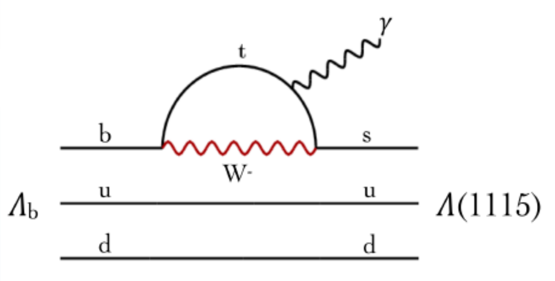


  - Transverse asymmetry in $B^0 \to K^{*0}ee$. JHEP 04 (2015) 064
    - Angular analysis at low q^2 of the virtual photon decay (pollution from C_9, C_{10})
  - Time-dependent analysis of $B \to f_{CP}\gamma$ decays, e.g.
    - $B_s^0 \to \phi\gamma$ Phys. Rev. Lett. 118 (2017) 021801
    - $B^0 \to K_s\pi^+\pi^-\gamma$
  - Angular analysis of radiative b-baryon decays, e.g.
    - $\Lambda_b \to \Lambda^{(*)}\gamma$
    - $\Xi_b \to \Xi^{(*)}\gamma$

New results presented today

arXiv:1904.06697

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



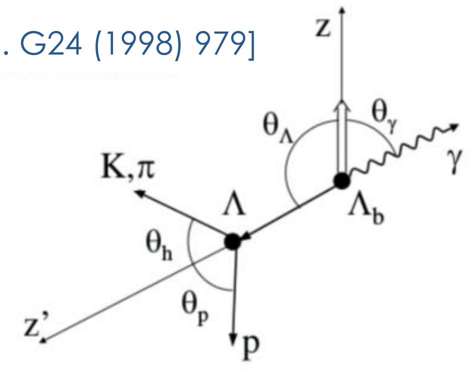
- Search of this decay using 2016 data (1.7 fb^{-1}).
- SM predictions for BR($\Lambda_b^0 \to \Lambda\gamma$) in the range (0.06-1)·$10^{-5}$.
  - [Eur. Phys. J. C59 (2009) 861, JHEP 12 (2011) 67, Commun. Theor. Phys. 58 (2012) 872, PRD 96 (2017) 053006]
- Sensitivity to C_7, C_7' through angular distributions.

$$\Gamma(\theta_p) = \frac{1}{4}(1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p)$$

$$\alpha_\Lambda = 0.642 \pm 0.013 \; [PDG\ 2016]$$

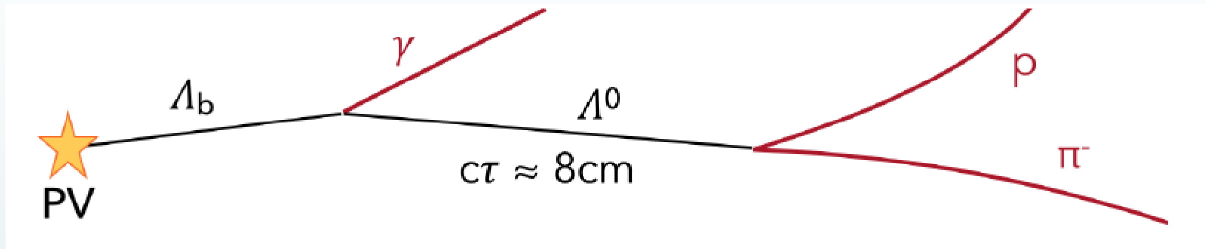
Experimental prospects at LHCb: [arXiv:1902.04870v2]

[J. Phys. G24 (1998) 979]

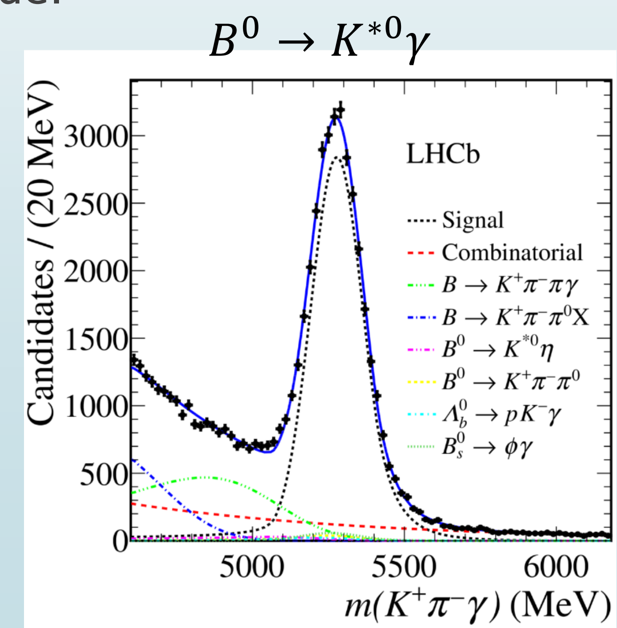


arXiv:1904.06697

- Challenge: no Λ_b vertex because Λ is long lived and no direction from the γ cluster.



- Signal/background separation using XGBoost.
- Used $B^0 \to K^{*0}\gamma$ as normalisation mode.
  - 32670 ± 290 candidates.



$$\frac{N(\Lambda_b^0 \to \Lambda\gamma)}{N(B^0 \to K^{*0}\gamma)} = \frac{f_{\Lambda_b^0}}{f_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} \times \frac{\mathcal{B}(\Lambda \to p\pi^-)}{\mathcal{B}(K^{*0} \to K^+\pi^-)} \times \frac{\epsilon(\Lambda_b^0 \to \Lambda\gamma)}{\epsilon(B^0 \to K^{*0}\gamma)}$$

From LHCb measurement arXiv:1902.06794
From PDG
From simulation and calibration samples

arXiv:1904.06697

- Signal excess with 5.6 σ significance.
  - 65 ± 13 candidates.
  - **First observation!**
- Branching fraction within the range of SM predictions.

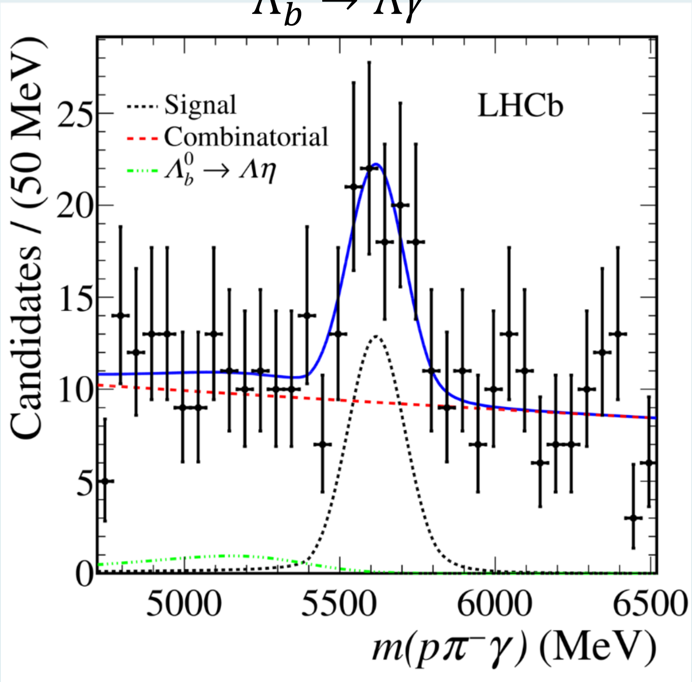
$$\mathcal{B}(\Lambda_b \to \Lambda\gamma) = (7.1 \pm 1.6 \pm 0.6 \pm 0.7) \cdot 10^{-6}$$

statistical

systematic

systematic from external measurements

$\Lambda_b^0 \to \Lambda\gamma$

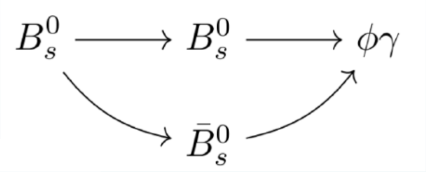


Systematic uncertainties

Source	Uncertainty (%)
Data/simulation agreement	7.7
Λ_b^0 fit model	3.0
$B^0 \to K^{*0}\gamma$ backgrounds	2.7
Size of simulated samples	1.7
Efficiency ratio	1.4
Sum in quadrature	9.0
$f_{\Lambda_b^0}/f_{B^0}$	8.7
Input branching fractions	3.0
Sum in quadrature	9.2

arXiv:1905.06284

Time-dependent analysis of $B_s^0 \to \phi\gamma$



- Access to the photon polarisation through the measurement of mixing-induced and CP-violating observables in the decay rate.

$$\Gamma(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \boldsymbol{A^{\Delta}}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm \boldsymbol{C}\cos(\Delta m_s t) \mp \boldsymbol{S}\sin(\Delta m_s t)\right]$$

- A^{Δ} and S are sensitive to the photon polarisation (C_7, C_7'), while C is related to direct CP asymmetry.
  - $\Delta\Gamma_s$ and Δm_s are the decay width and mass differences between B_s^0 CP eigenstates.
- Previous analysis without flavour tagging information (no separation between B_s^0 and $\bar{B}_s^0$) with Run-1 data:

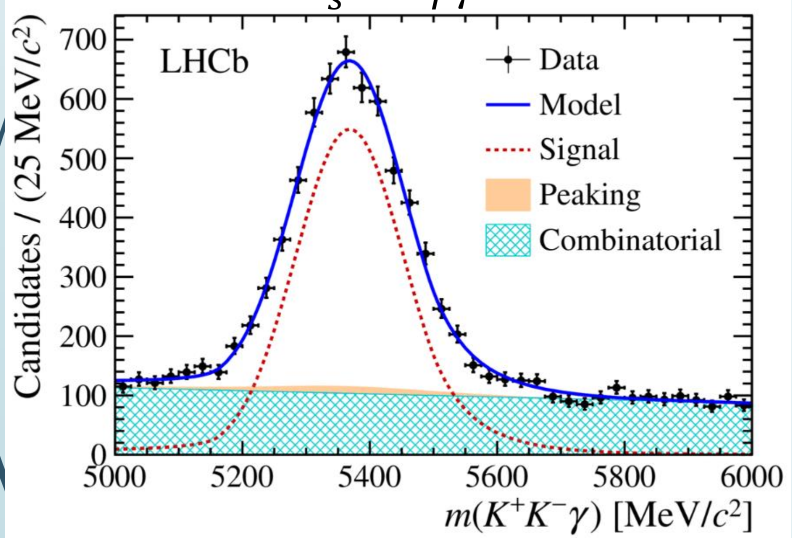
$$A^{\Delta} = -0.98^{+0.46}_{-0.52}{}^{+0.23}_{-0.20}$$

Phys. Rev. Lett. 118 (2017) 021801

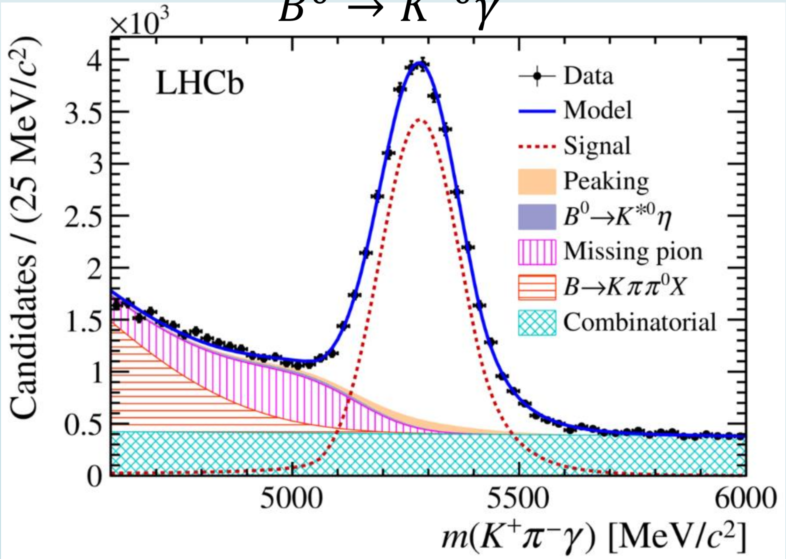
- In agreement with SM prediction $A^{\Delta}_{SM} = 0.047^{+0.029}_{-0.025}$ [PLB 664 (2008) 174] [arXiv:1905.06284](https://arxiv.org/abs/1905.06284)

- Now including flavour tagging information and re-analysing Run-1 data (3 fb^{-1}) with optimized reconstruction, selection and photon identification algorithms.
  - **First measurement of $\mathcal{C}$ and $\mathcal{S}$ in B_s^0 decays.**
- 5110 ± 90 $B_s^0 \to \phi\gamma$ candidates (~4.2k in previous analysis).
- Use $B^0 \to K^{*0}\gamma$ as control channel for the decay time acceptance.
  - 33860 ± 250 candidates.

$B_s^0 \to \phi\gamma$



$B^0 \to K^{*0}\gamma$



- Simultaneous unbinned ML fit to both decays, using per-candidate decay time resolution (σ_t) and flavour-tagging information (q, ω).

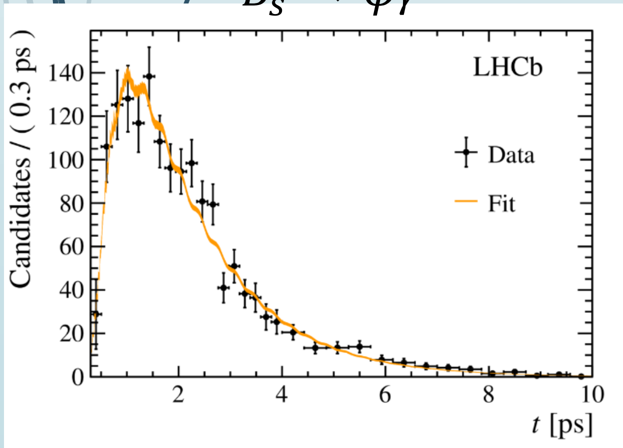
$$\Gamma_{B_s^0 \to \phi\gamma}(t') = \Gamma(t', q|\omega) \otimes \{A(t_i) R(t, t'|\sigma_t)\}$$

- Results:

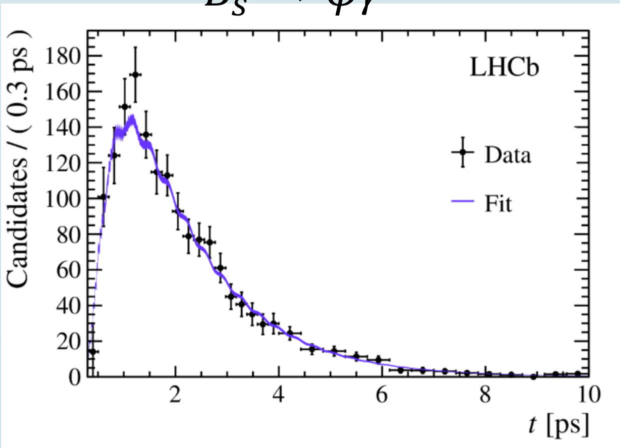
$$\boldsymbol{S = 0.43 \pm 0.30 \pm 0.11}$$
$$\boldsymbol{C = 0.11 \pm 0.29 \pm 0.11}$$
$$\boldsymbol{A^{\Delta} = -0.67^{+0.37}_{-0.41} \pm 0.17}$$

  - Compatible with SM [PLB 664 (2008) 174-179] at 1.3, 0.3, 1.7 σ, respectively.
  - Statistical limited. Dominant source of systematic uncertainties related to the determination of the decay-time acceptance.

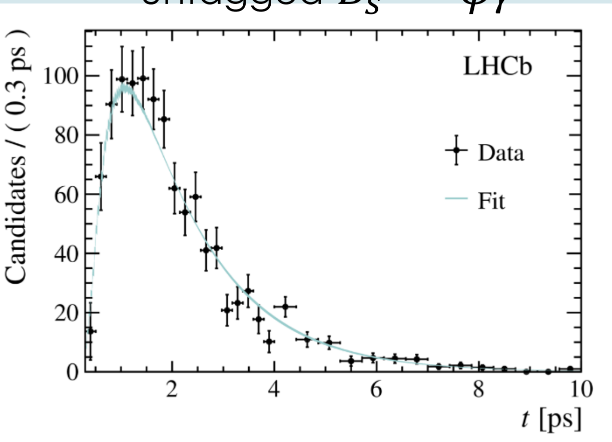
$B_s^0 \to \phi\gamma$



$\bar{B}_s^0 \to \phi\gamma$

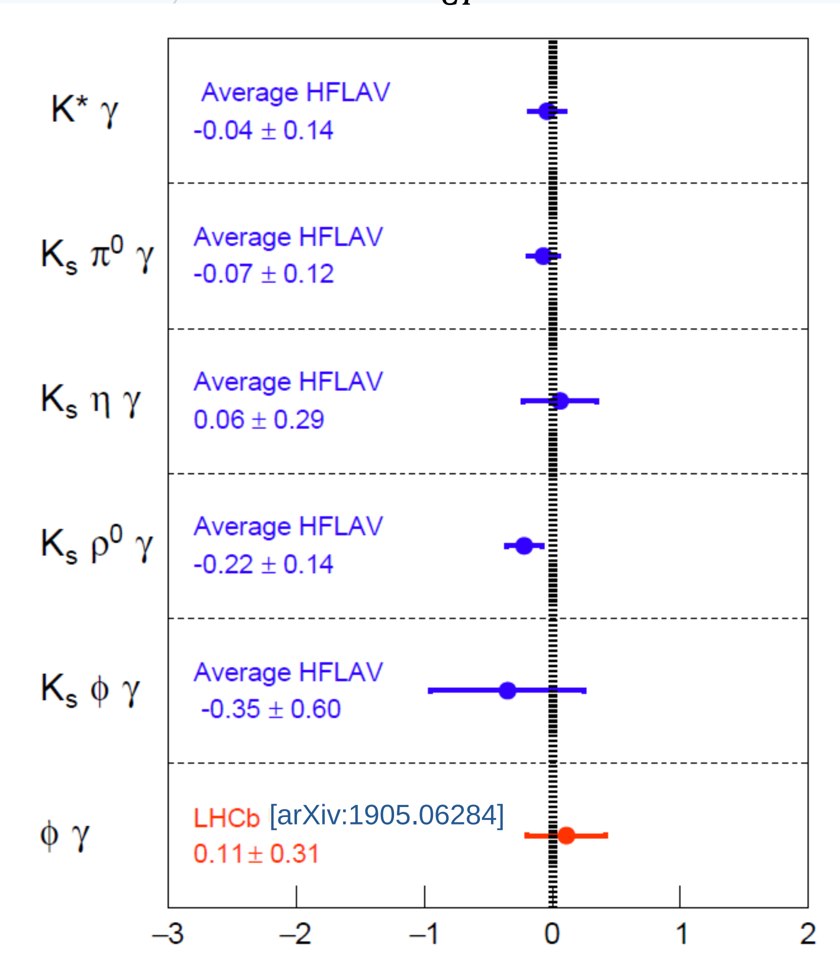


untagged $B_s^0 \to \phi\gamma$

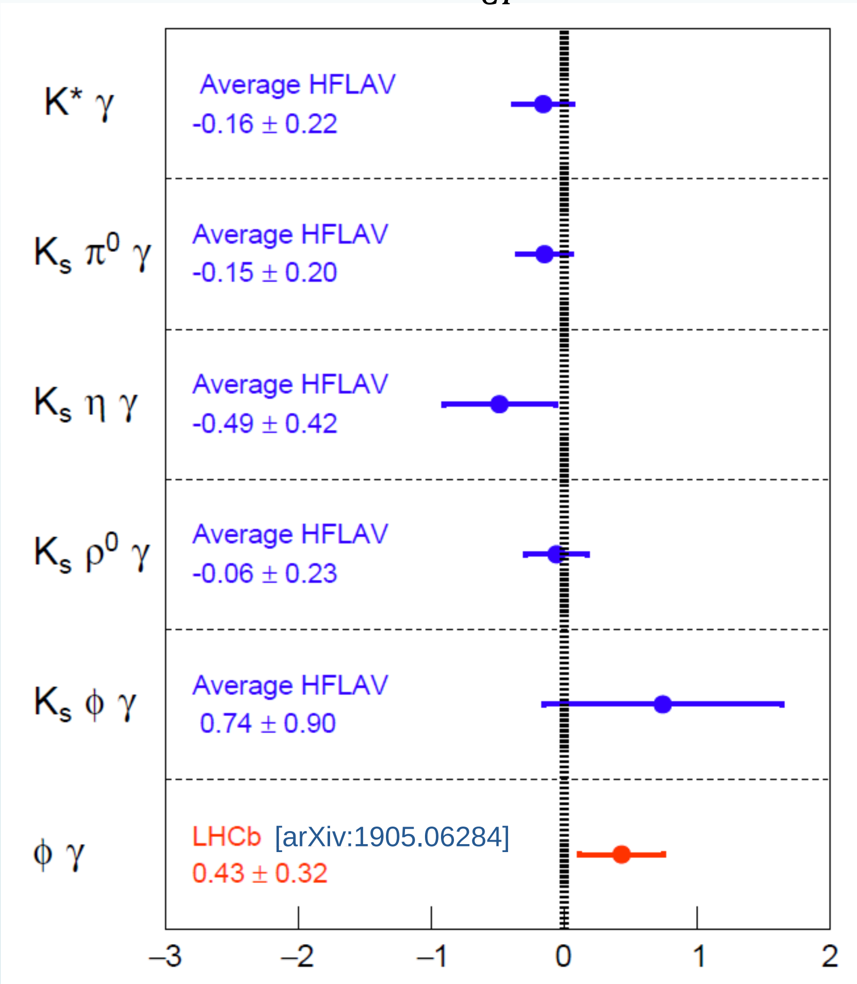


- Competitive with previous measurements from B-factories.

C_{CP}

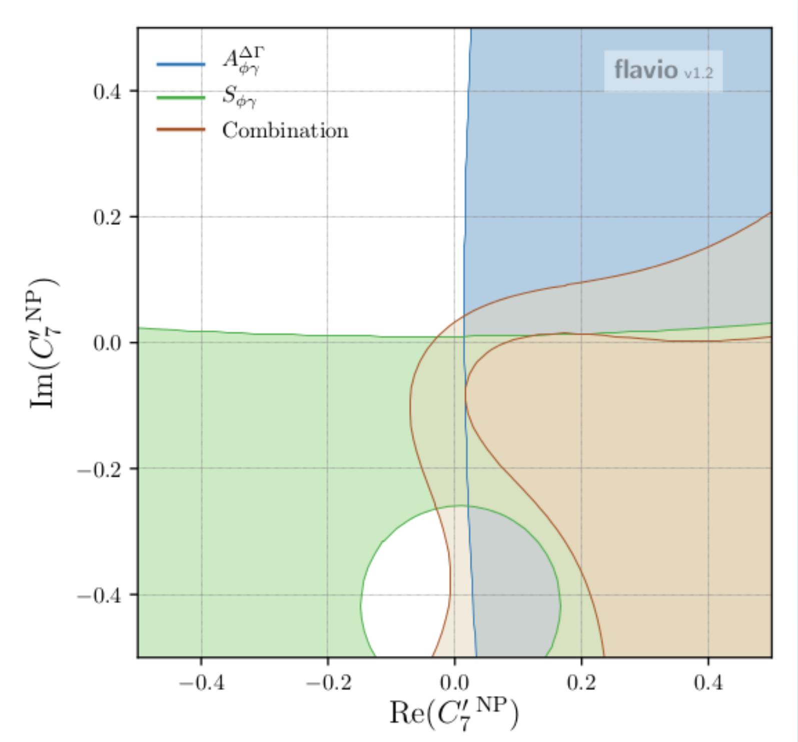


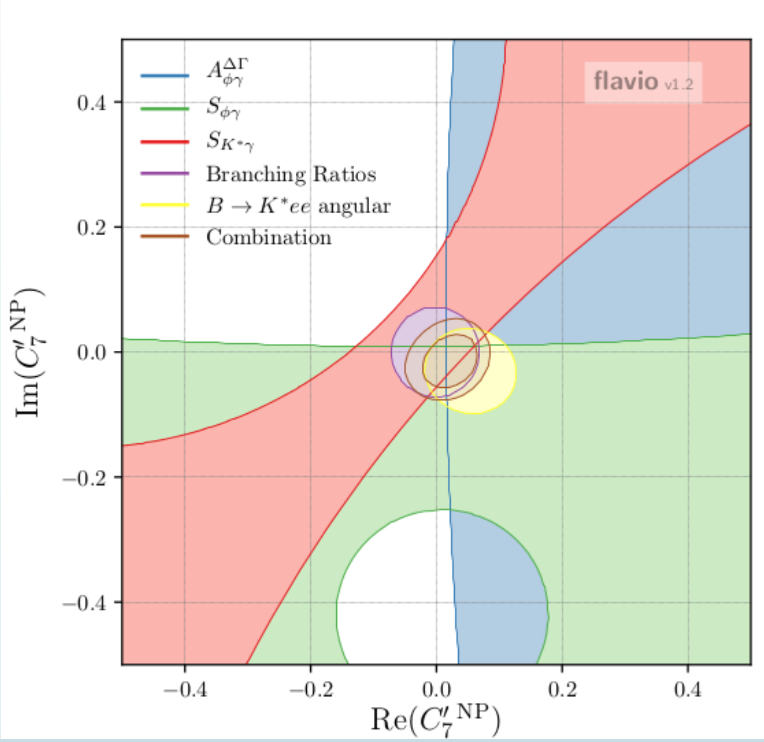
S_{CP}



NP constraints

- A^{Δ} and S provide complementary constrains in the complex plane.
- Constraints to C_7' using Flavio [arXiv:1810.08132]
  - Inputs: from LHCb [arXiv:1905.06284, JHEP 04 (2015) 064] and HFLAV.

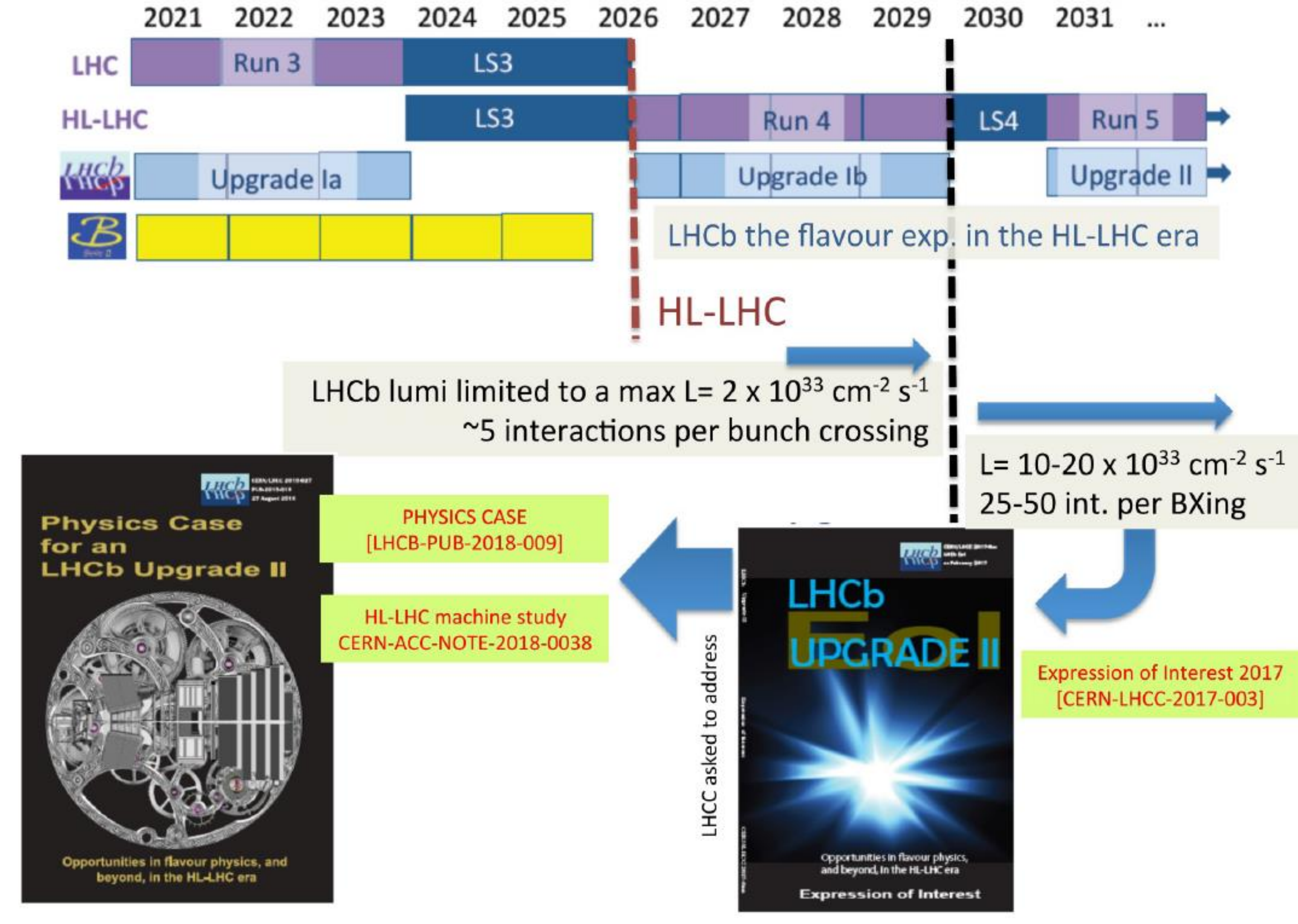




Summary

- Radiative b-decays allow to probe NP at large energy scales through indirect measurements.
- The photon polarisation can be measured in several ways.
  - Interesting observable that puts constraints on C_7' (right-handed part).
- Lastest results from LHCb:
  - First observation of $\Lambda_b^0 \to \Lambda\gamma$, opening the possibility of measuring the photon polarisation in b-baryon decays.
  - Time-dependent analysis of $B_s^0 \to \phi\gamma$. Constraints on C_7' and first measurent of C and S in a B_s^0 decay.
- Many more results with Run-2 data coming soon.

Backup slides


2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 ...
LHC
Run 3
LS3
HL-LHC
LS3
Run 4
LS4
Run 5
Upgrade Ia
Upgrade Ib
Upgrade II
LHCb the flavour exp. in the HL-LHC era
HL-LHC
LHCb lumi limited to a max L= 2 x 10^33 cm^-2 s^-1
~5 interactions per bunch crossing
L= 10-20 x 10^33 cm^-2 s^-1
25-50 int. per BXing
Physics Case for an LHCb Upgrade II
Opportunities in flavour physics, and beyond, in the HL-LHC era
PHYSICS CASE
[LHCB-PUB-2018-009]
HL-LHC machine study
CERN-ACC-NOTE-2018-0038
LHCC asked to address
LHCb
UPGRADE II
EoI
Opportunities in flavour physics, and beyond, in the HL-LHC era
Expression of Interest
Expression of Interest 2017
[CERN-LHCC-2017-003]

Physics case for and LHCb Upgrade II

Decay mode	Yield (300 fb^{-1})	Statistical sensitivity on measurement
$B_s \to \phi\gamma$	800k	0.02 on A^{Δ}
$B^0 \to K_s^0 \pi\pi\gamma$	200k	Competitive on S_{CP}
$B^+ \to K\pi\pi\gamma$		Photon polarisation <1%
$B^0 \to K^{*0} ee$	20k	2% on A_T
$\Lambda_b \to \Lambda^0 (p\pi)\gamma$	10k	α_γ <2%
$\Xi_b \to \Xi^- (\Lambda^0 \pi)\gamma$		α_γ <10%

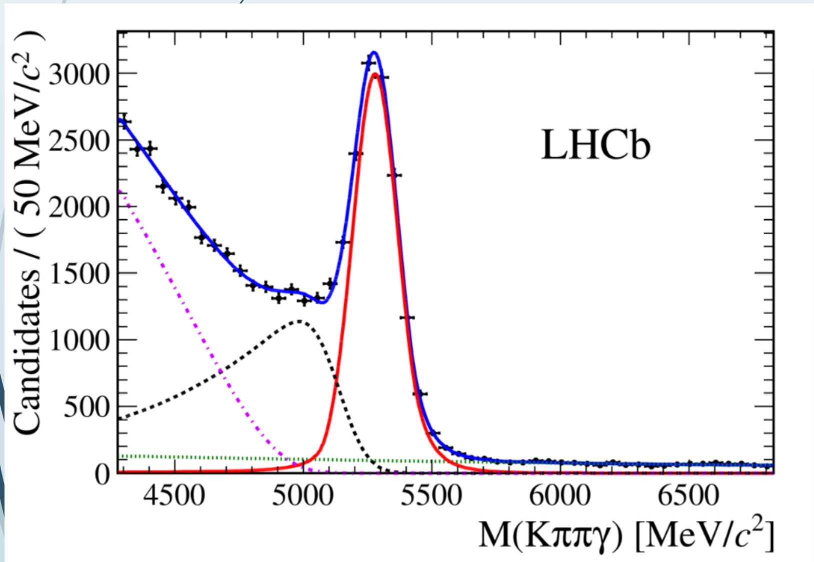
Previous published measurements

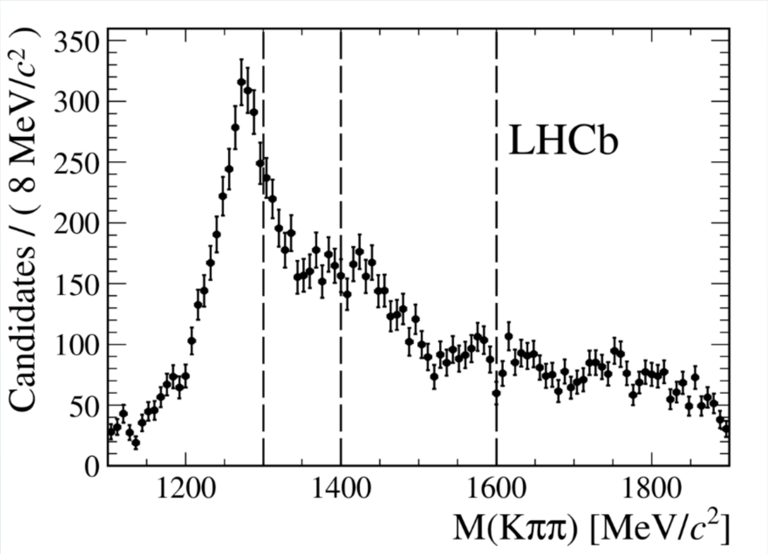
- Measurement of the ratio of branching fractions $\mathcal{B}(B^0 \to K^{*0}\gamma)/\mathcal{B}(B_s^0 \to \phi\gamma)$. Phys. Rev. D85 (2012) 112013
- Measurement of the ratio of branching fractions $\mathcal{B}(B^0 \to K^{*0}\gamma)/\mathcal{B}(B_s^0 \to \phi\gamma)$ and the direct CP asymmetry in $B^0 \to K^{*0}\gamma$. Nucl. Phys. B 867 (2013) 1
- Observation of photon polarization in the $b \to s\gamma$ transition. Phys. Rev. Lett. 112 (2014) 161801
- Angular analysis of the $B^0 \to K^{*0}e^+e^-$ decay in the low-q^2 region. JHEP 04 (2015) 064
- Search for the rare decays $B^0 \to J/\psi\gamma$ and $B_s^0 \to J/\psi\gamma$. Phys. Rev. D 92 (2015) 112002
- First experimental study of photon polarization in radiative B_s^0 decays. Phys. Rev. Lett. 118 (2017) 021801

First observation of photon polarisation in $B^+ \rightarrow K^+\pi^+\pi^-\gamma$

Phys. Rev. Lett. 112 (2014) 161801

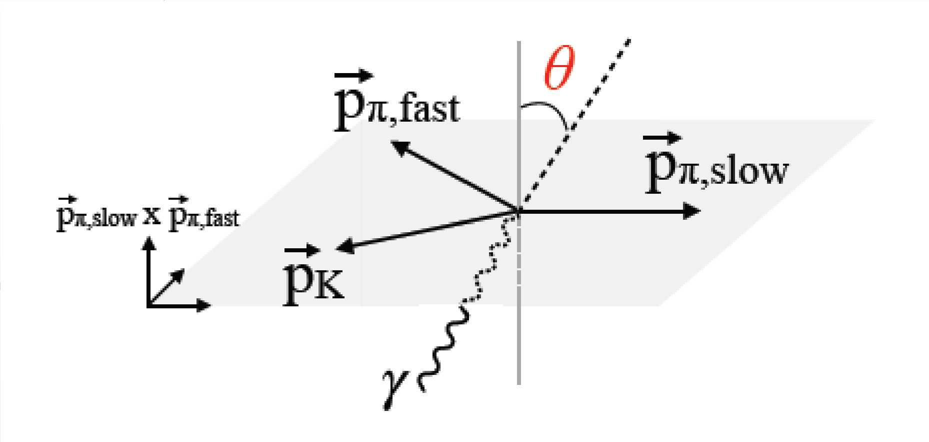
- Run-1 data (3 fb^{-1}). ~14k candidates with all intermediate resonances of $K\pi\pi$ in [1.1, 1.9] GeV/c^2 mass range.





The photon polarisation can be inferred from the polarisation of the K resonance.

- Need three tracks in the final state to form a parity odd triple product.



[Gronau et al., PRL 88 (2002) 051802]

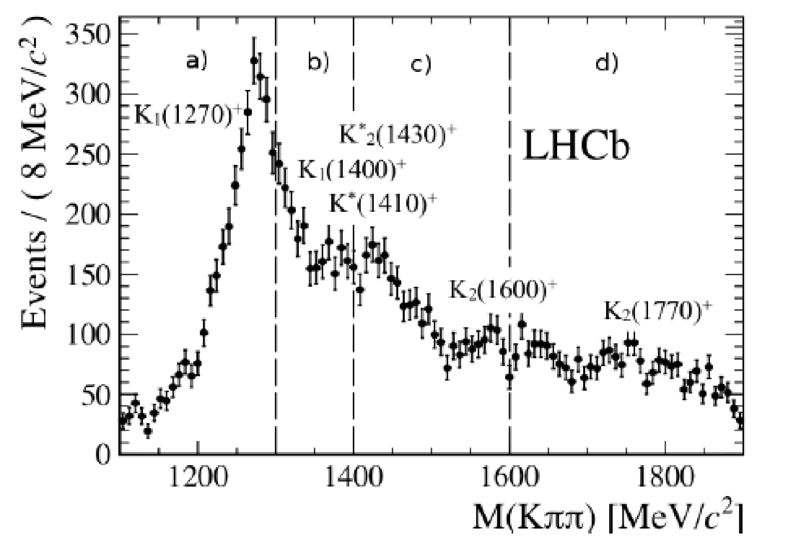
For a mixture of resonances:

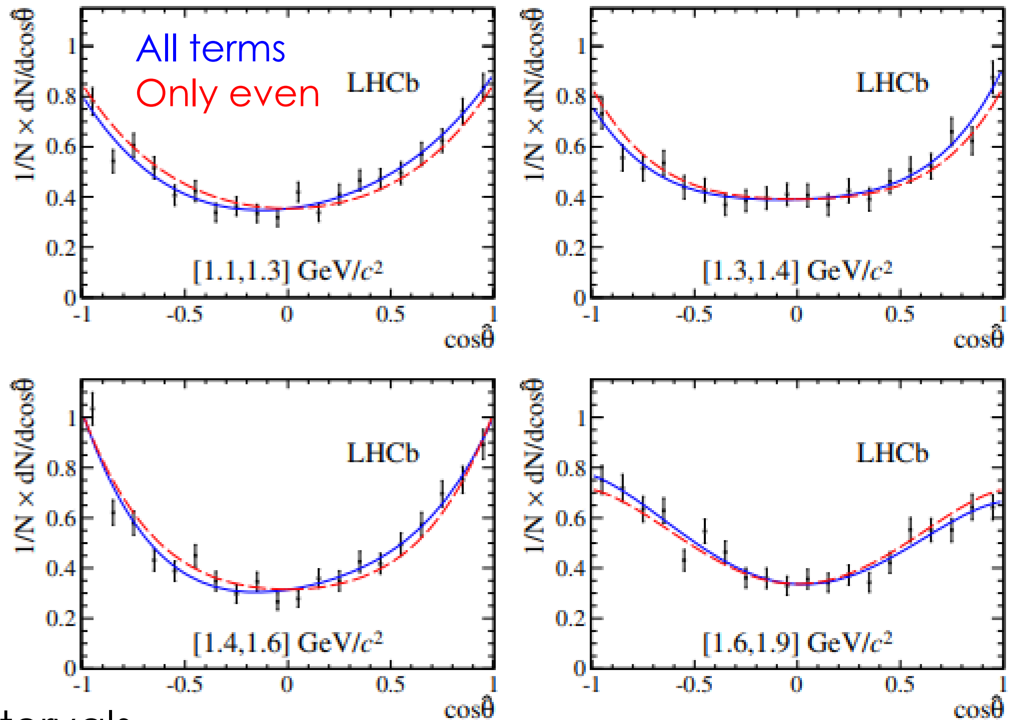
$$\frac{d\Gamma}{ds\,ds_{13}\,ds_{23}\,d\cos\theta} \propto \sum_{i=0,2,4} a_i(s, s_{13}, s_{23})\cos^i\theta + \lambda_\gamma \sum_{j=1,3} a_j(s, s_{13}, s_{23})\cos^j\theta$$

Define an up-down asymmetry, proportional to the photon polarisation parameter, λ_γ

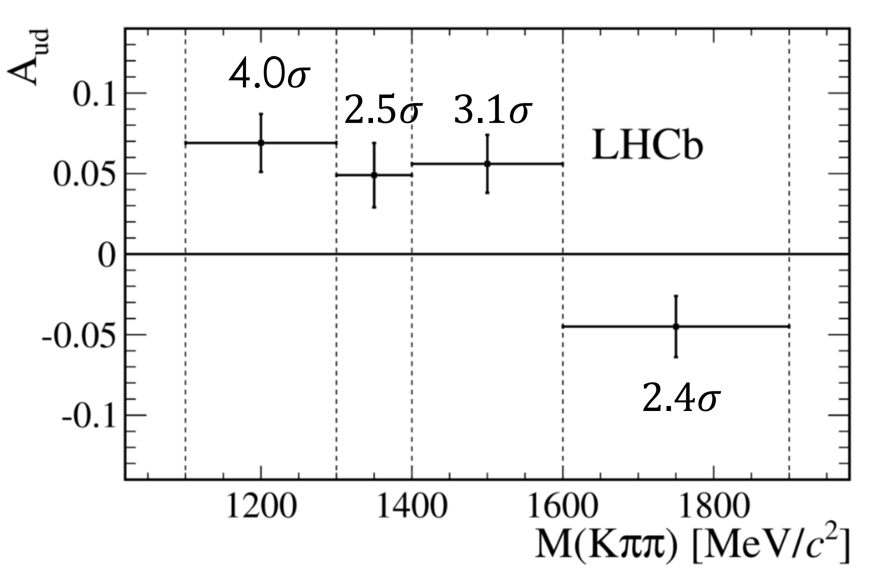
[Gronau and Pirjol, PRD 96 (2017) 013002]

$$\mathcal{A}_{\mathrm{ud}} \equiv \frac{\int_0^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} - \int_{-1}^0 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}}{\int_{-1}^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}} = C\lambda_\gamma$$





Asymmetry measured in four K_{res} mass intervals



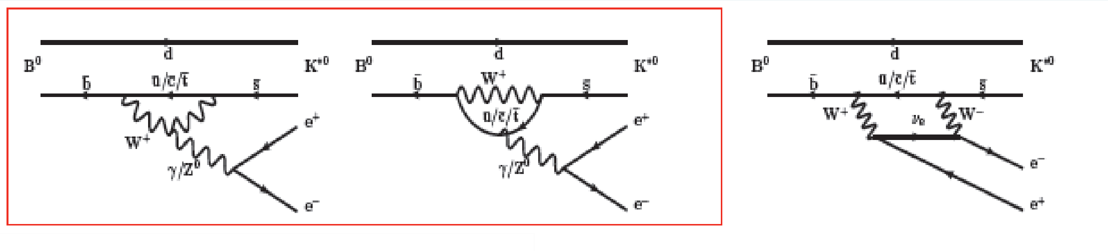
First direct observation of a non-zero photon polarisation in $b \to s\gamma$, with 5.2σ significance.

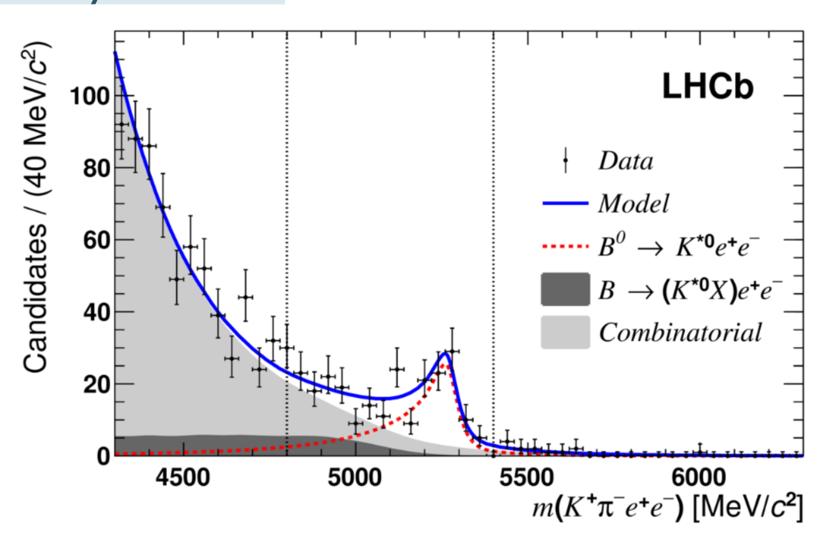
Theory input and full amplitude analysis (ongoing) are needed to determine the exact value of the polarisation.

$B^0 \to K^{*0} ee$ in the low q² region

JHEP 04 (2015) 064

- Run-1 data (3 fb⁻¹). 150 $B^0 \to K^{*0}e^+e^-$candidates.
- Angular analysis at very low $m(ee)$. Sensitive to photon polarisation in the limit $m(ee) \to 0$.

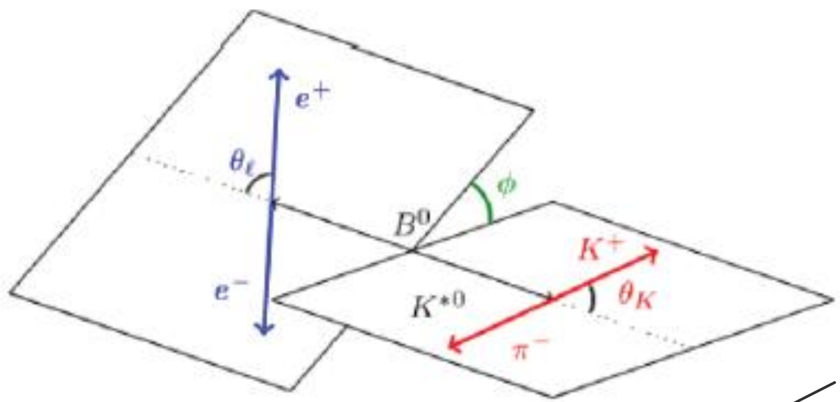




Used $B^0 \to J/\psi(e^+e^-)K^{*0}$ as control channel

Simplified angular distribution with 4 observables.

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



Angular analysis with $\cos\theta_l$, $\cos\theta_k$, $\tilde{\phi}$

Sensitive to photon polarisation

[Krüger, Matias, Phys. Rev. D 71 (2005) 094009]
[Becirevic, Schneider, J. Nucl. Phys. B 09 (2011) 004]

$$F_\mathrm{L} = \frac{|A_0|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$$

$$A_\mathrm{T}^{(2)} = \frac{|A_\perp|^2-|A_\parallel|^2}{|A_\perp|^2+|A_\parallel|^2}$$

$$A_\mathrm{T}^{\mathrm{Re}} = \frac{2\mathcal{R}e(A_{\parallel L}A^*_{\perp L}+A_{\parallel R}A^*_{\perp R})}{|A_\parallel|^2+|A_\perp|^2}$$

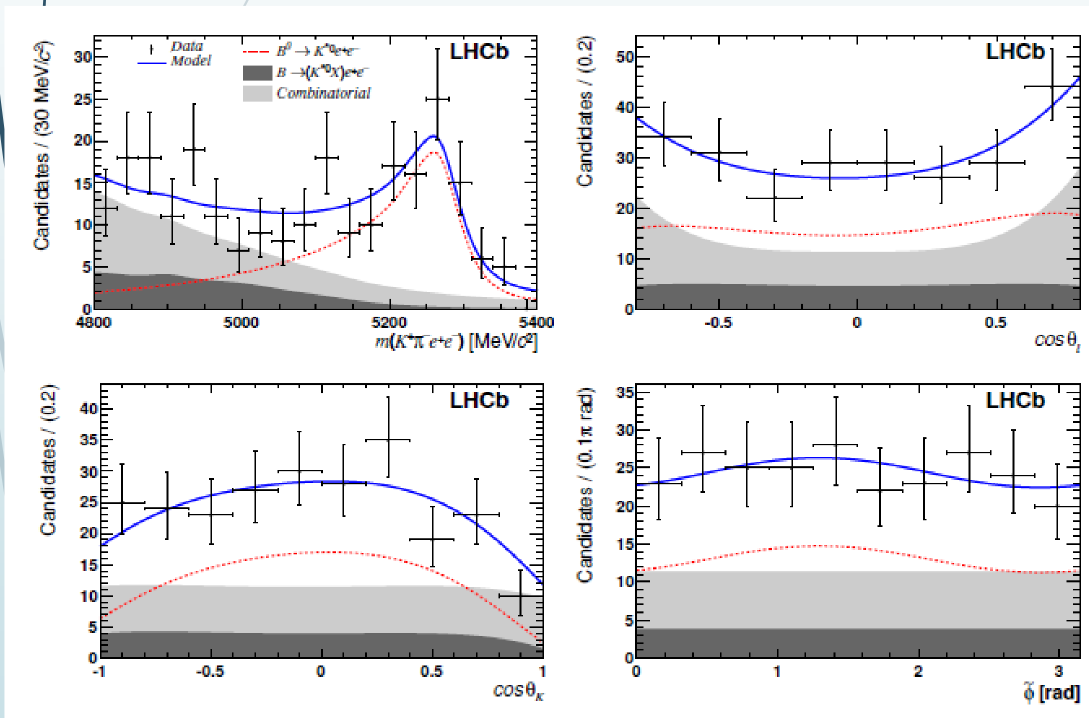
$$A_\mathrm{T}^{\mathrm{Im}} = \frac{2\mathcal{I}m(A_{\parallel L}A^*_{\perp L}+A_{\parallel R}A^*_{\perp R})}{|A_\parallel|^2+|A_\perp|^2},$$

Approximation:

$$\lim_{q^2\to 0} \mathrm{A}_\mathrm{T}^{(2)} = \frac{2\mathcal{R}e(C_7C_7'^{})}{|C_7|^2+|C_7'|^2}$$

$$\lim_{q^2\to 0} \mathrm{A}_\mathrm{T}^{\mathrm{Im}} = \frac{2\mathcal{I}m(C_7C_7')}{|C_7|^2+|C_7'|^2}$$

Angular analysis for di-lepton q^2 in [20, 1120] MeV/c^2.
Reconstruction challenges with electrons:
lower reconstruction efficiencies and bremmsstrahlung recovery.



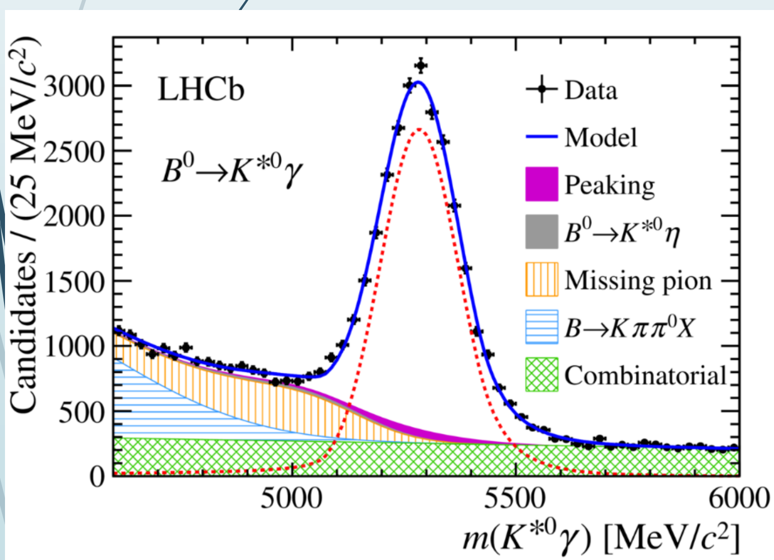
$$
\begin{aligned}
F_{\rm L} &= 0.16 \pm 0.06 \pm 0.03 \\
A_{\rm T}^{(2)} &= -0.23 \pm 0.23 \pm 0.05 \\
A_{\rm T}^{\rm Im} &= +0.14 \pm 0.22 \pm 0.05 \\
A_{\rm T}^{\rm Re} &= +0.10 \pm 0.18 \pm 0.05,
\end{aligned}
$$

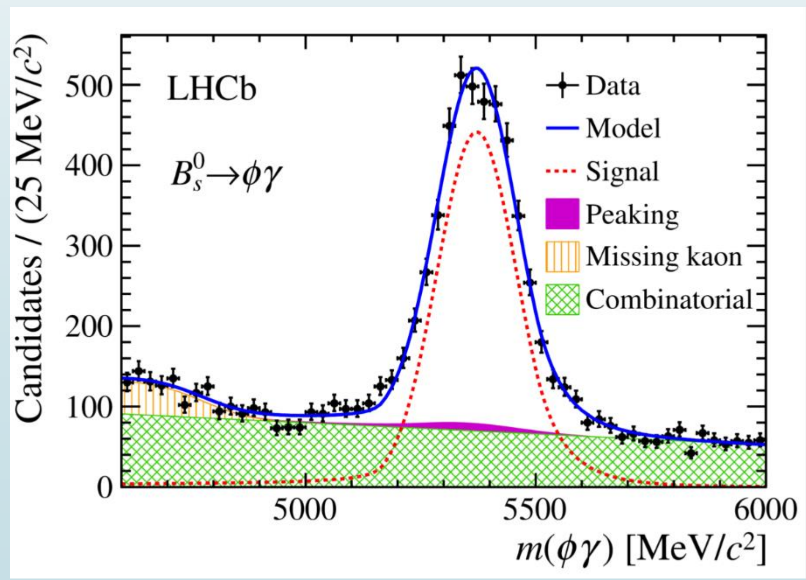
Compatible with SM predictions

Time-dependent decay rate of $B_s^0 \to \phi\gamma$

Phys. Rev. Lett. 118 (2017) 021801

- Run-1 data (3 fb^{-1}). 4.2k $B_s^0 \to \phi\gamma$ candidates.
- 25.8k $B^0 \to K^{*0}\gamma$ used as control sample for decay time acceptance (simultaneous fit).

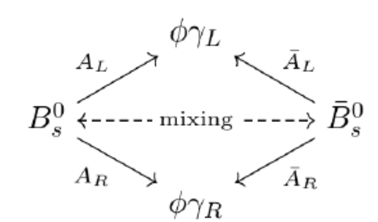




Direct access to the photon polarisation through the time-dependent decay rate of $B_s^0 \to \phi\gamma$.

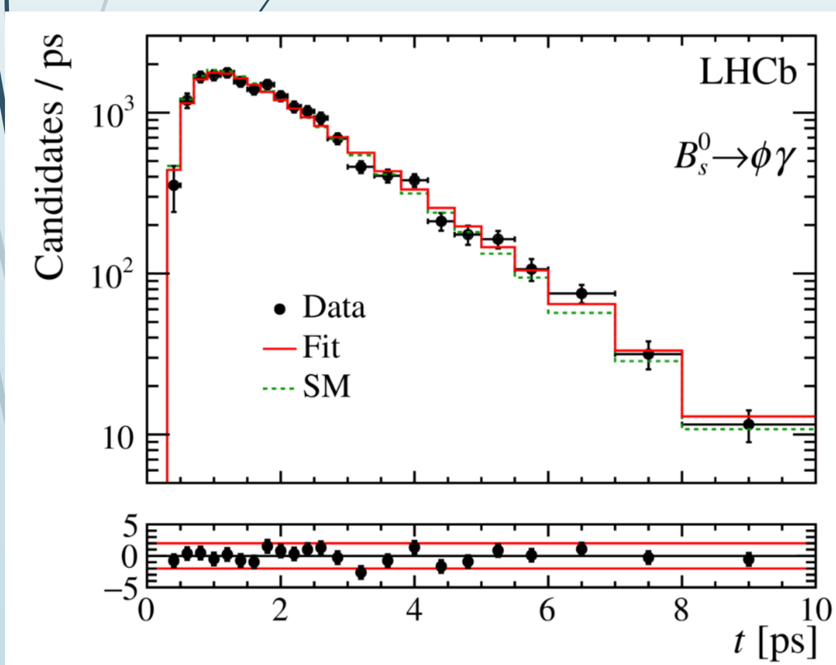
$$\Gamma(B^0_{(s)} \to f^{CP}\gamma) \sim e^{-\Gamma_{(s)}t}\left\{\cosh\frac{\Delta\Gamma_{(s)}t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_{(s)}t}{2} \pm \mathcal{C}\cos\Delta m_{(s)}t \mp \mathcal{S}\sin\Delta m_{(s)}t\right\}.$$

Mixing/decay interference



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

An untagged measurement was performed, so only $\mathcal{A}^{\Delta}$ was measured:



$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}(\text{stat.})^{+0.23}_{-0.20}(\text{syst.})$$

Compatible with SM at 2.6σ

SM prediction: $\mathcal{A}^{\Delta} = 0.047^{+0.029}_{-0.025}$

[Muheim et al., PRB 664 (2008) 174]

In Left-Right Symmetric model $\mathcal{A}^{\Delta}\sim 0.7$