Radiative b-hadron decays at LHCb

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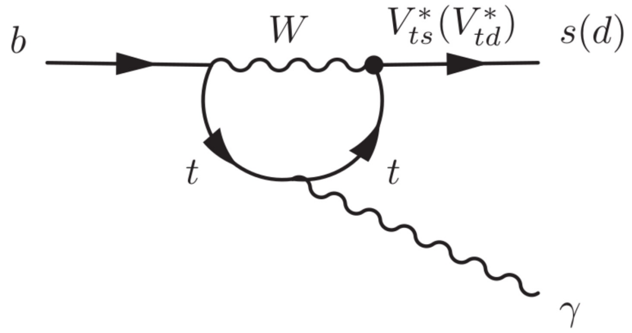
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

AGENCIA ESTATAL DE INVESTIGACIÓN

Introduction: radiative decays of beauty hadrons

- SM: proceed at leading order through b → sγ **one-loop electromagnetic penguin transitions**
- BSM models predict **additional one-loop contributions** that can introduce sizeable effects on the dynamics of the transition
- We use Weak Effective Field Theory to encode possible NP effects in the Wilson coefficients $\mathcal{H}_{eff} \propto V_{ts}^* V_{tb}(C_7 O_7 + C_7' O_7')$
- The LHC era has brought observations of new radiative b-hadron **decay modes** and **precise measurements** of
  - asymmetries $\quad \not{C}\not{P} \rightarrow Im(C_7)$
  - branching fractions $\quad \mathscr{B}(A \rightarrow BC) \rightarrow (|C_7|^2 + |C_7'|^2)$
  - helicity structure $\quad \gamma_{(L/R)} \rightarrow |C_7'/C_7|$



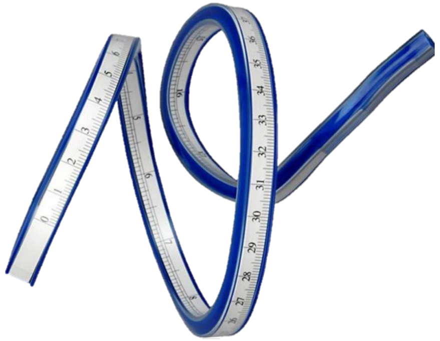
Contents

- New results in radiative b-hadron decays at LHCb since ICHEP 2022

- $B_s^0 \to \mu^+\mu^-\gamma$
  Search

- $B_s^0 \to K^+K^-\gamma$
  Amplitude analysis

- $\Lambda_b^0 \to pK^-\gamma$
  Amplitude analysis



Using 2016-2018 data
5.4 fb^{-1}

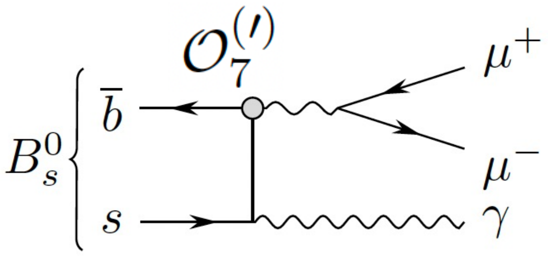
Using run 1 + run 2 data
9 fb^{-1}

Search of $B_s^0 \to \mu^+\mu^-\gamma$ – Introduction

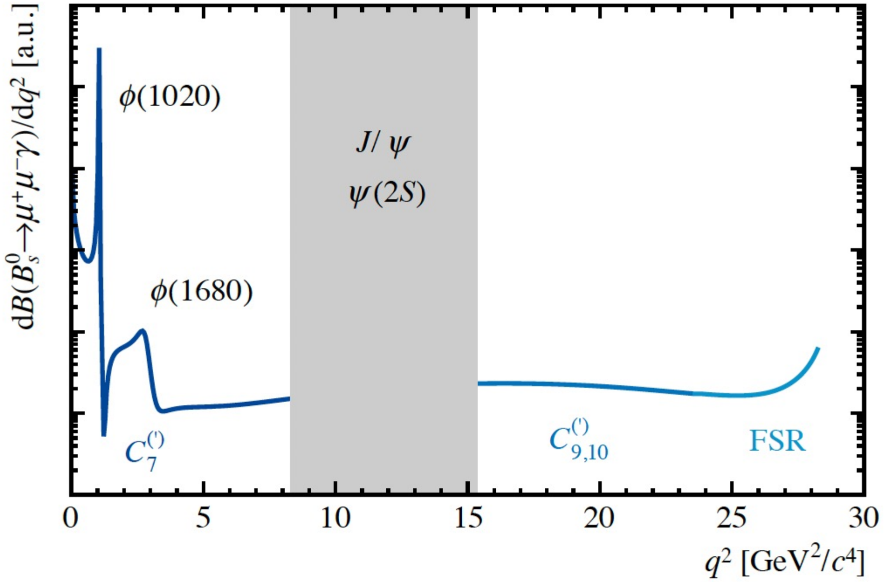
JHEP07(2024)101

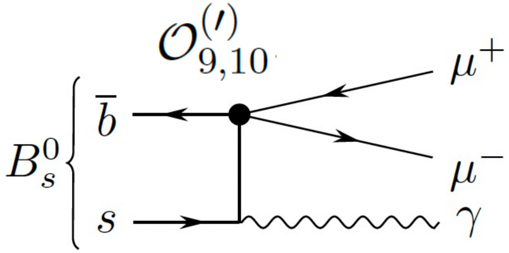
- Very rare decay, SM predictions
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{low\ q^2} = (8.3 \pm 1.3)\times10^{-9}$
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{high\ q^2} = (8.9 \pm 1.0)\times10^{-10}$

  JHEP11(2017)184
- Previously probed at LHCb as a partially reconstructed background of $B_s^0 \to \mu\mu$, but limited to high dimuon mass squared (q^2) region Phys.Rev.Lett.128.041801 PhysRevD.105.012010
- Sensitive to a wide set of operators dominant in the different q^2 regions

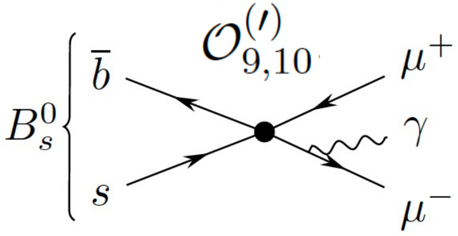


electromagnetic-dipole operators





vector and axial-vector interactions

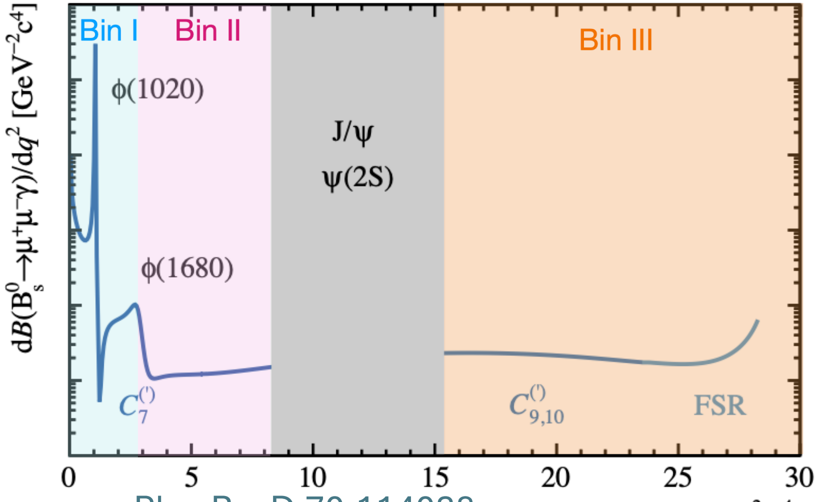


final state radiation

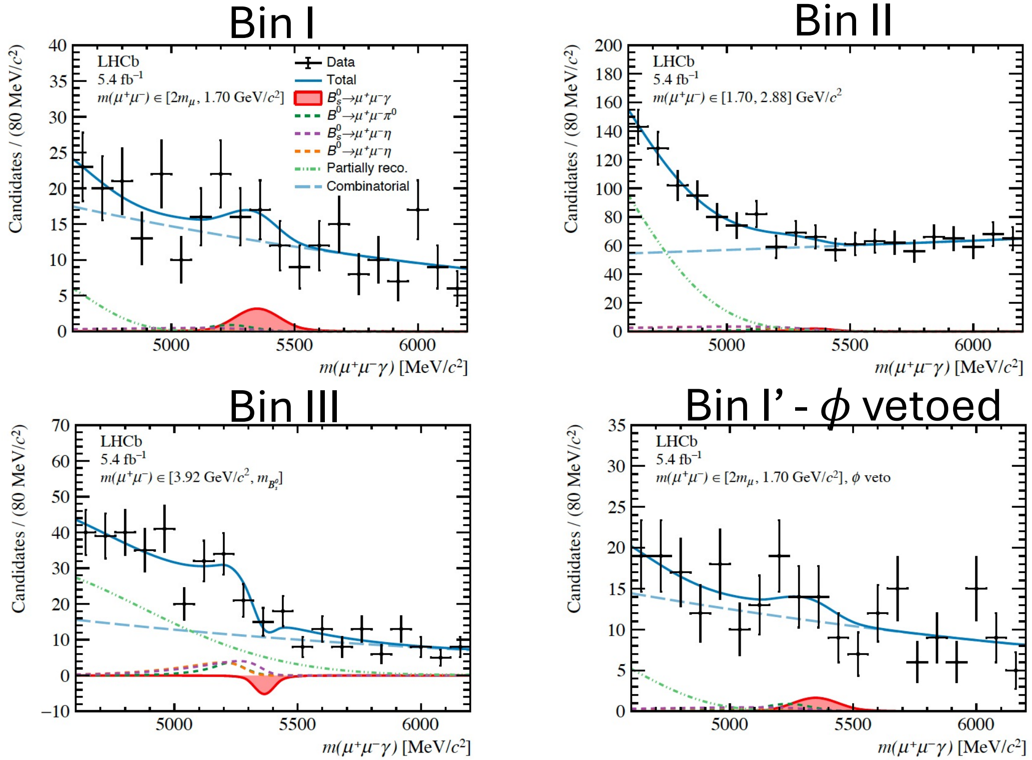
Search of $B_s^0 \to \mu^+\mu^-\gamma$ – Strategy

JHEP07(2024)101

- Search preformed in regions of q^2
- Normalized to $B_s^0 \to J/\psi\,(\to \mu^+\mu^-)\eta(\to \gamma\gamma)$ decay
- Uses $B_s^0 \to \phi(\to K^+K^-)\gamma$ to control of data-simulation discrepancies
- Cut based preselection
- Two Multilayer Perceptron classifiers
- Consistent with background-only hypothesis at $< 1\sigma$



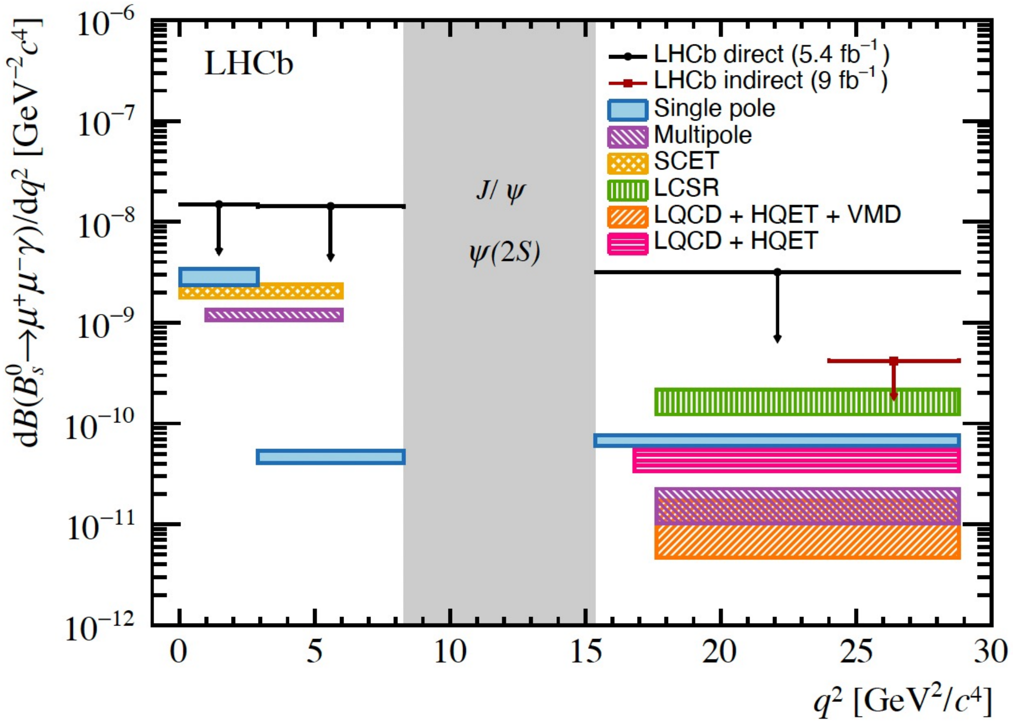
PhysRevD.70.114028



Search of $B_s^0 \to \mu^+\mu^-\gamma$ – Results

JHEP07(2024)101

- Limits are set using the CLs method, yielding at 90% CL:
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{Bin\ I} < 3.6 \times 10^{-8}$
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{Bin\ II} < 6.5 \times 10^{-8}$
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{Bin\ III} < 3.4 \times 10^{-8}$
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{Bin\ I,\phi\ veto} < 2.9 \times 10^{-8}$
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{Combined} < 2.5 \times 10^{-8}$



Amplitude analysis $B_s^0 \to K^+K^-\gamma$ – Introduction

arXiv 2406.00235, submited to JHEP

- Amplitude analysis of the $B_s^0 \to K^+K^-\gamma$ decay to study the hadronic structure
- First observation of the radiative B_s^0 decay to the orbitally excited mesons
- Phase space fully described by $(m_{KK}, \cos\theta_{KK})$
- Radiative scalar beauty meson decay → free of the S-wave amplitude
- Interferences of odd- and even-spin resonances cancel out
- Detector asymmetries cancelled out by folding over θ_{KK}

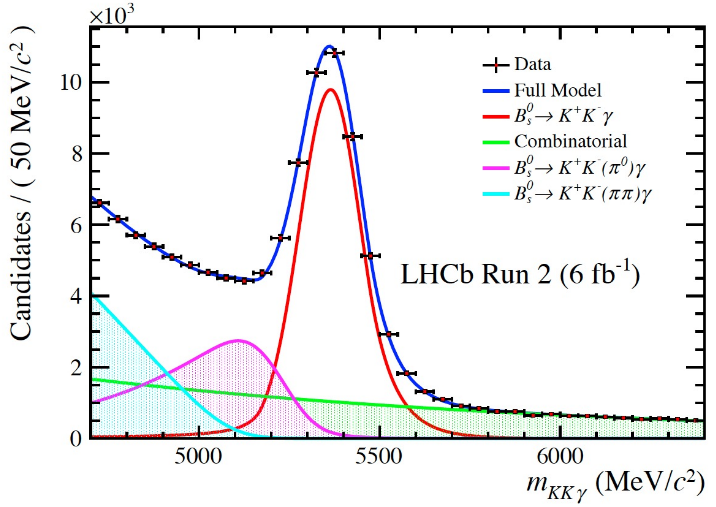
$$\cos\theta_{KK} \to |\cos\theta_{KK}|$$

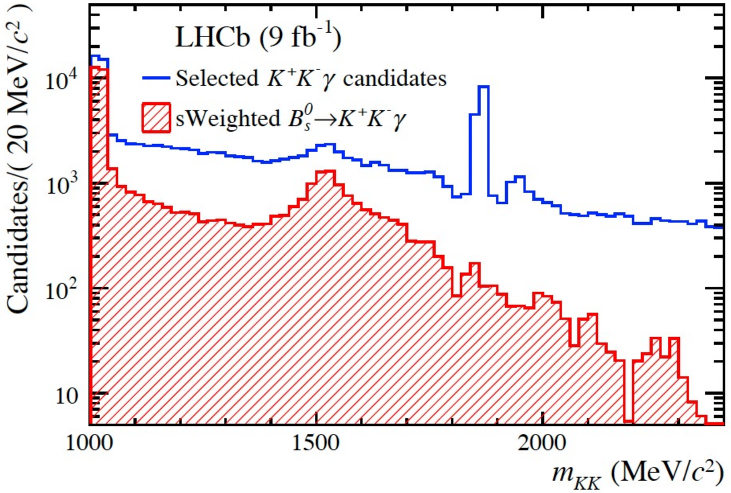
State	J^{PC}
$\phi(1020)$	1^{--}
$f_2'(1525)$	2^{++}
$\phi(1680)$	1^{--}
$f_2(1270)$	2^{++}
$\phi_3(1850)$	3^{--}
$f_2(2010)$	2^{++}
$(\mathrm{KK})_{\mathrm{NR}}$	1^{--}

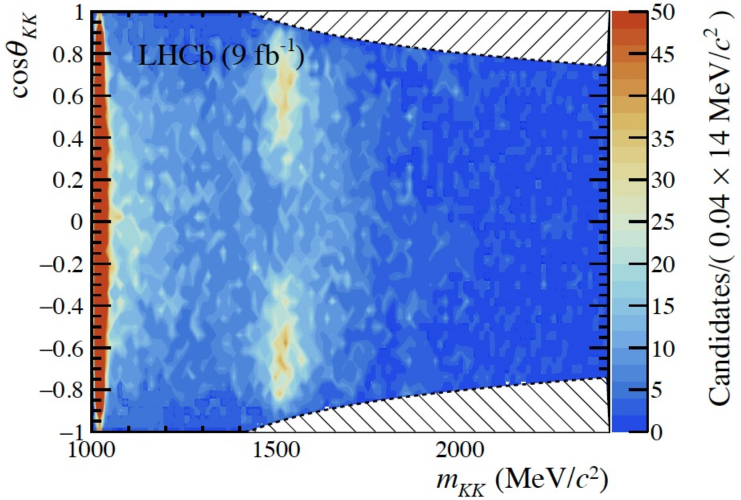
Amplitude analysis $B_s^0 \to K^+K^-\gamma$ – Strategy

arXiv 2406.00235, submited to JHEP

- Fit to m_{B_s} and sPlot technique for background subtraction







- Parametrization of acceptance in $\varepsilon(m_{KK}, \theta_{KK})$
  - Including the effect of anti-charm veto $m_{K\gamma} > 2000\, MeV/c$
- Parametrization of mis-ID backgrounds
- Fit of the amplitudes using isobar amplitude model approach

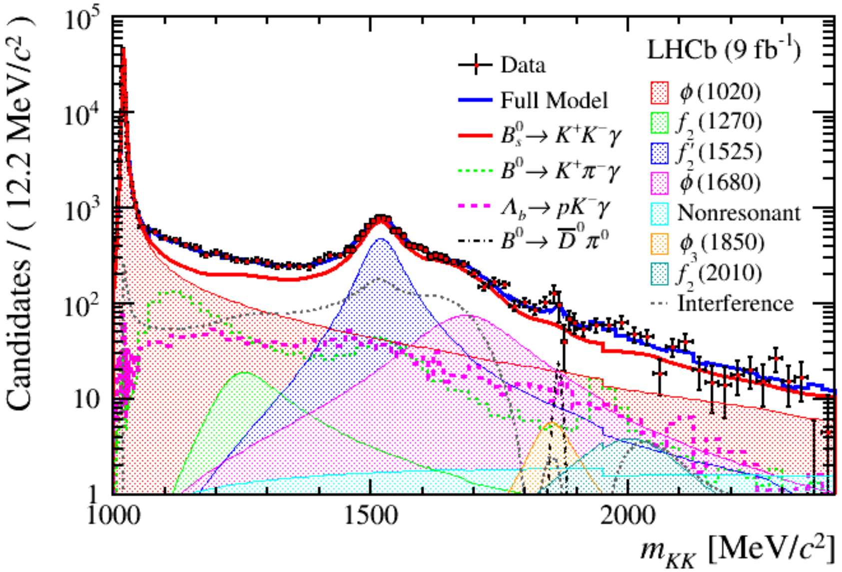
Amplitude analysis $B_s^0 \to K^+K^-\gamma$ – Fit

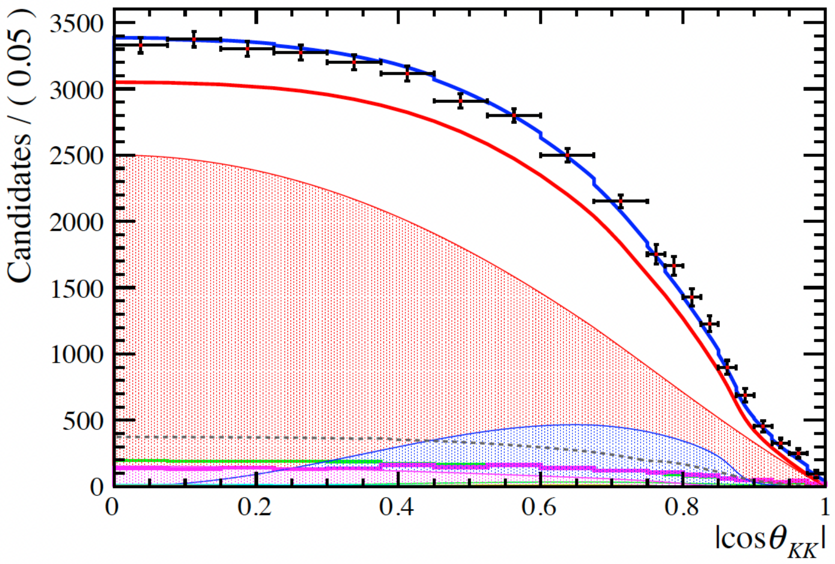
arXiv 2406.00235, submited to JHEP

- MisID backgrounds included in the fit $\mathcal{P}(m_{KK},\theta_{KK}) = \mathcal{N}_S\mathcal{P}_S + \sum_{BKG}\mathcal{N}_{BKG}\mathcal{P}_{BKG}$
- Amplitude model

$$\overbrace{\mathcal{P}_S(m_{KK},\theta_{KK})}^{Signal\ PDF} = \overbrace{\varepsilon(m_{KK},\theta_{KK})}^{Selection\ acceptance} \cdot \overbrace{\left|\sum_R c_R \cdot \mathcal{F}_R\mathcal{F}_B\mathcal{BW}_R(m_{KK};\mu_R,\Gamma_R)\cdot d_{10}^{J_R}(\theta_{KK})\right|^2}^{Isobar\ KK\ model}$$

- 20 free parameters
  - Yields
  - Isobar factors + phases
  - Mass and width of $\phi(1020), f_2'(1525)$
  - Radius parameter of $\phi(1020)$





Amplitude analysis $B_s^0 \to K^+K^-\gamma$ – Results

arXiv 2406.00235, submited to JHEP

- Fit fractions, relative branching fractions and overall tensor contribution reported for the preferred fit solution
- Mass and width of $\phi(1020)$, $f_2'(1525)$ in agreement with world average
- Radius parameter of $\phi(1020)$

State	Fit fraction (%)	Relative fit fraction (%)	Phase (deg.)
$\phi(1020)$	$70.3\ ^{+0.9}_{-1.0}\ ^{+1.0}_{-1.2}$	100	0 (fixed)
$f_2(1270)$	$0.8 \pm 0.3\ ^{+0.2}_{-0.3}$	$1.2\ ^{+0.4}_{-0.3}\ ^{+0.3}_{-0.5}$	$-55\ ^{+13}_{-17}\ ^{+25}_{-17}$
$f_2'(1525)$	$12.1\ ^{+0.6}_{-0.5}\ ^{+0.9}_{-0.4}$	$17.3\ ^{+0.8}_{-0.7}\ ^{+1.3}_{-0.5}$	0 (fixed)
$\phi(1680)$	$3.8\ ^{+0.6}_{-0.5} \pm 0.7$	$5.4\ ^{+0.9}_{-0.6}\ ^{+1.0}_{-1.1}$	$137\ ^{+5}_{-6} \pm 8$
$\phi_3(1850)$	$0.3\ ^{+0.2}_{-0.1}\ ^{+0.2}_{-0.1}$	$0.4\ ^{+0.3}_{-0.2}\ ^{+0.3}_{-0.2}$	$-61\ ^{+16}_{-13}\ ^{+13}_{-12}$
$f_2(2010)$	$0.4 \pm 0.2\ ^{+0.2}_{-0.1}$	$0.6\ ^{+0.3}_{-0.2}\ ^{+0.3}_{-0.2}$	$43\ ^{+30}_{-24}\ ^{+52}_{-59}$
$(KK)_{NR}$	$0.5\ ^{+0.4}_{-0.2}\ ^{+0.3}_{-0.2}$	$0.6\ ^{+0.5}_{-0.3}\ ^{+0.5}_{-0.3}$	$165\ ^{+6}_{-16} \pm 9$

$$\frac{\mathcal{B}(B_s^0 \to f_2(1270)\gamma)}{\mathcal{B}(B_s^0 \to \phi(1020)\gamma)} = 0.25^{+0.09}_{-0.07}\ (\text{stat.})^{+0.06}_{-0.10}\ (\text{syst.}) \pm 0.03\ (\text{BR}),$$

$$\frac{\mathcal{B}(B_s^0 \to f_2'(1525)\gamma)}{\mathcal{B}(B_s^0 \to \phi(1020)\gamma)} = 0.194^{+0.009}_{-0.008}\ (\text{stat.})^{+0.014}_{-0.005}\ (\text{syst.}) \pm 0.005\ (\text{BR})$$

$$\frac{\mathcal{B}(B_s^0 \to \phi(1680)\gamma)}{\mathcal{B}(B_s^0 \to \phi(1020)\gamma)} \times \mathcal{B}(\phi(1680) \to K^+K^-) = 0.026^{+0.004}_{-0.003}\ (\text{stat.}) \pm 0.005\ (\text{syst.}).$$

overall tensor contribution

$$\mathcal{F}_{\{f_2\}} = 16.8 \pm 0.5\,(\text{stat}) \pm 0.7\,(\text{syst})\%$$

Amplitude analysis $\Lambda_b^0 \to pK^-\gamma$ – Introduction

JHEP 06 (2024) 098

- Amplitude analysis of $\Lambda_b^0 \to pK^-\gamma$ to study the hadronic structure
- First observation of this decay
- Helpful for the interpretation of a variety of measurements in the $\Lambda_b^0 \to pK^-l^+l^-$ spectrum
  - LFU, CP violation, Branching fractions
- Useful input for potential measurements of photon polarization
- Important feedback for low energy QCD theoretical description

Resonance	J^P
$\Lambda(1405)$	$1/2^-$
$\Lambda(1520)$	$3/2^-$
$\Lambda(1600)$	$1/2^+$
$\Lambda(1670)$	$1/2^-$
$\Lambda(1690)$	$3/2^-$
$\Lambda(1800)$	$1/2^-$
$\Lambda(1810)$	$1/2^+$
$\Lambda(1820)$	$5/2^+$
$\Lambda(1830)$	$5/2^-$
$\Lambda(1890)$	$3/2^+$
$\Lambda(2100)$	$7/2^-$
$\Lambda(2110)$	$5/2^+$
$\Lambda(2350)$	$9/2^+$

Amplitude analysis $\Lambda_b^0 \to pK^-\gamma$ – Method

JHEP 06 (2024) 098

- Fit to $m_{pK\gamma}$ and sPlot technique for background subtraction
- Phase space can be described by (m_{pK}, θ_p)
- Amplitude model using helicity formalism (detailed description in JHEP06(2020)116)

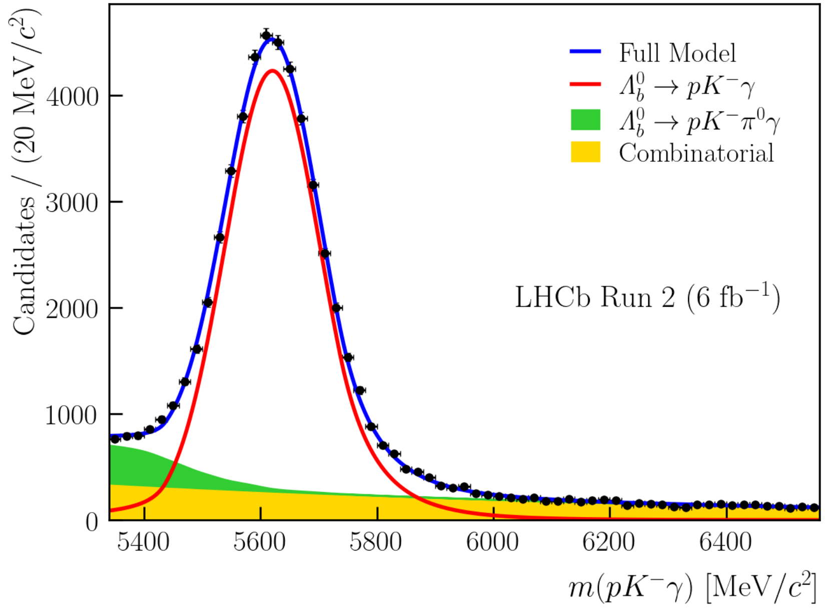
Amplitude for a given Λ state and fixed helicities $\lambda_\Lambda, \lambda_p, \lambda_\gamma$

$$\mathcal{A}(\Lambda, \lambda_\Lambda, \lambda_p, \lambda_\gamma) \propto \underbrace{d^{J_\Lambda}_{\lambda_p \lambda_\Lambda}(\theta_p)}_{\text{Wigner d matrix}} \times \sum_{L,S} \left[\underbrace{C_1^{\Lambda\gamma} C_2^{\Lambda\gamma} C_1^{pK^-} C_2^{pK^-}}_{\text{Clebsch-Gordans}} \underbrace{A_{LS}}_{\text{coupling}} \underbrace{\left(\frac{p}{M_{\Lambda_b^0}}\right)^L \left(\frac{q}{M_\Lambda}\right)^\ell}_{\text{orb. ang. mom. barriers}} \underbrace{B_L(p) B_\ell(q)}_{\text{Blatt-Weisskopf form factors}} \underbrace{\mathrm{BW}(m_{pK})}_{\text{lineshape}} \right]$$

The full decay rate

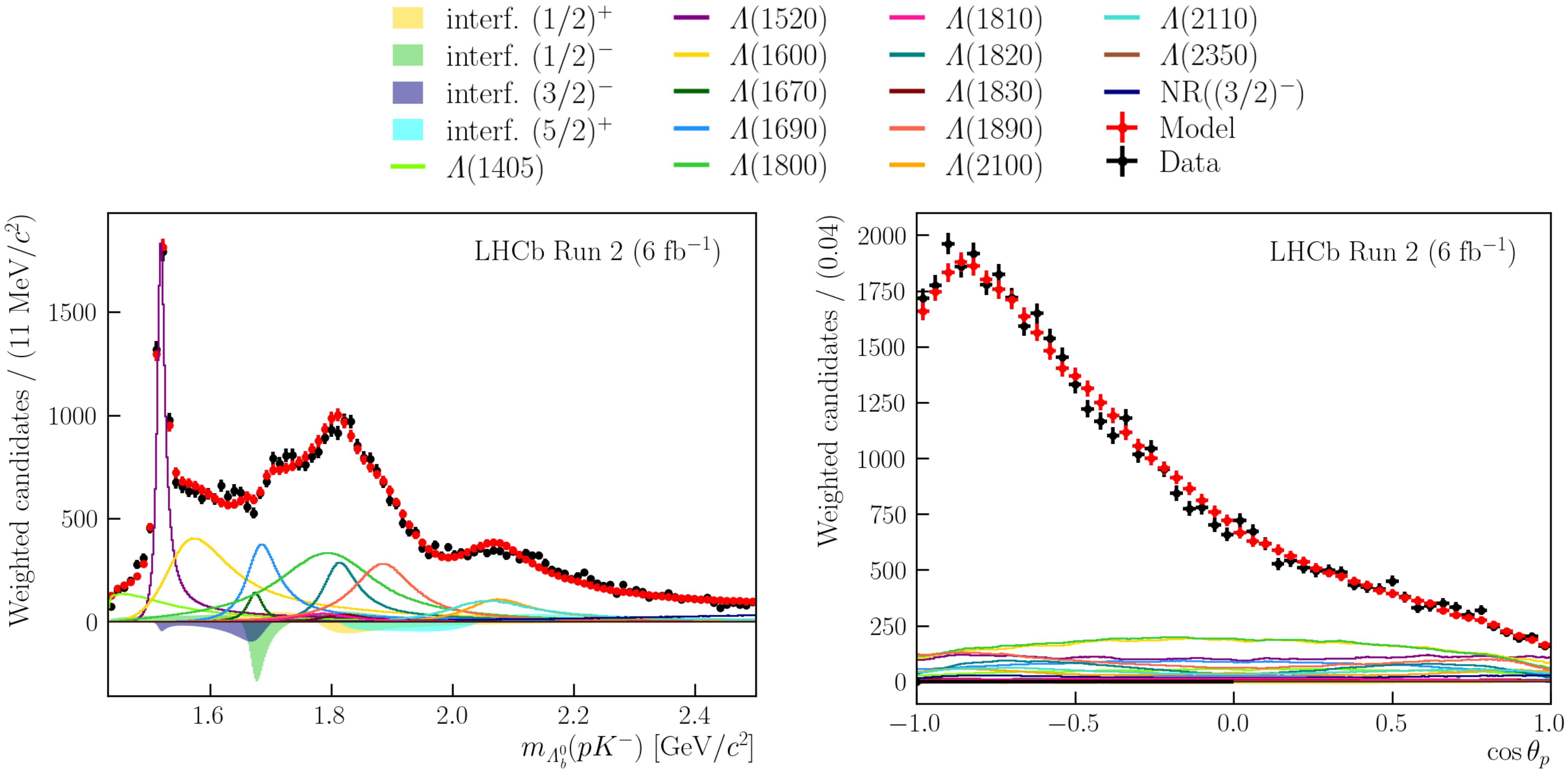
$$\sum_{\lambda_{\Lambda_b^0}, \lambda_p, \lambda_\gamma} \left| \sum_{\Lambda} \sum_{\lambda_\Lambda} d^{J_\Lambda}_{\lambda_p \lambda_\Lambda}(\theta_p) \times \sum_{L,S} \left[\text{constants} \quad \underbrace{h^\Lambda_{LS}}_{LS\text{ coupling}} \quad \text{barriers} \quad \text{line shape} \right] \right|^2$$

- Restricted to Λ resonances and one non-resonant component $J^P = \frac{3}{2}^-$



Amplitude analysis $\Lambda_b^0 \to pK^-\gamma$ – Fit results

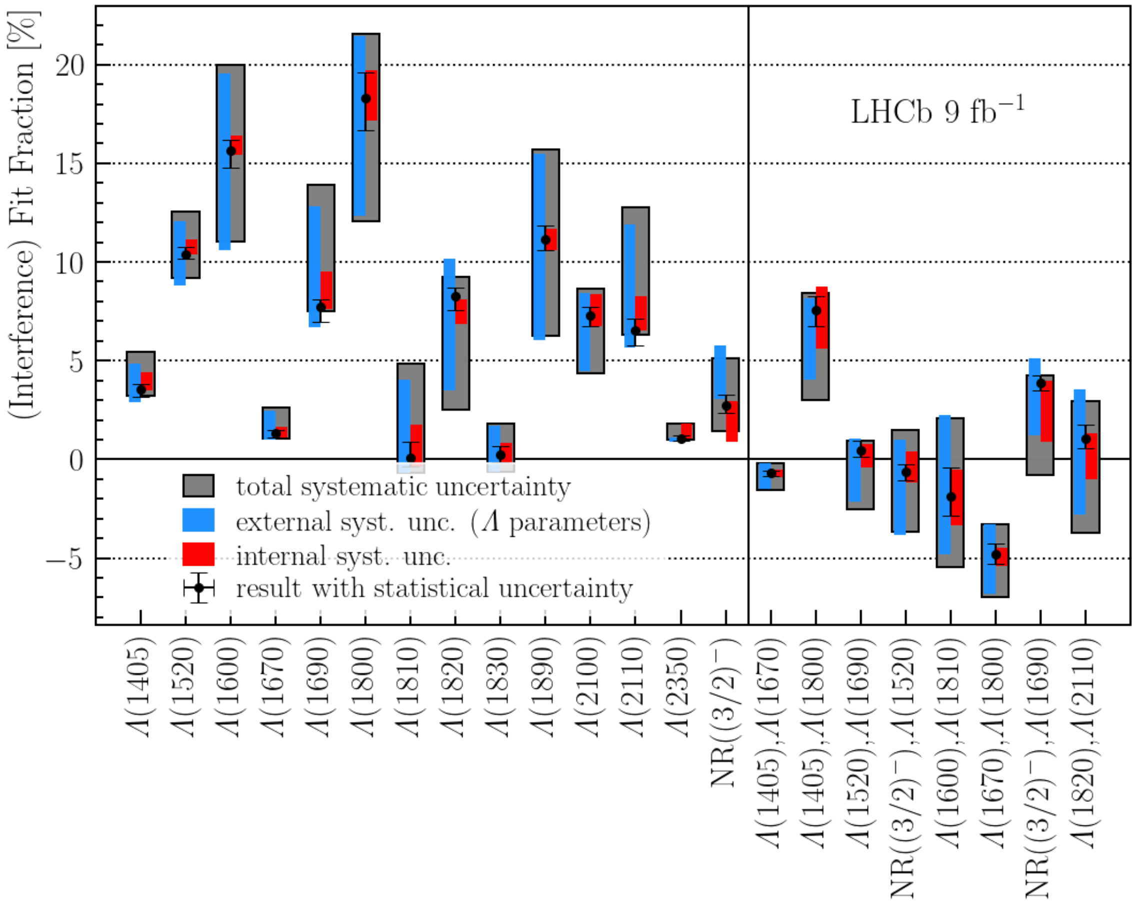
JHEP 06 (2024) 098



Amplitude analysis $\Lambda_b^0 \to pK^-\gamma$ – Results

JHEP 06 (2024) 098

- Fit fractions presented
  - Largely contributing: $\Lambda(1520), \Lambda(1600), \Lambda(1800), \Lambda(1890)$
  - Large interference between $\Lambda(1405) - \Lambda(1800)$
- Uncertainty dominated by external uncertainty in the masses and widths of the Λ resonances
- Stay tunned for Ulrik's talk to see $\Lambda_b^0 \to pK^-\mu\mu$ angular analysis!



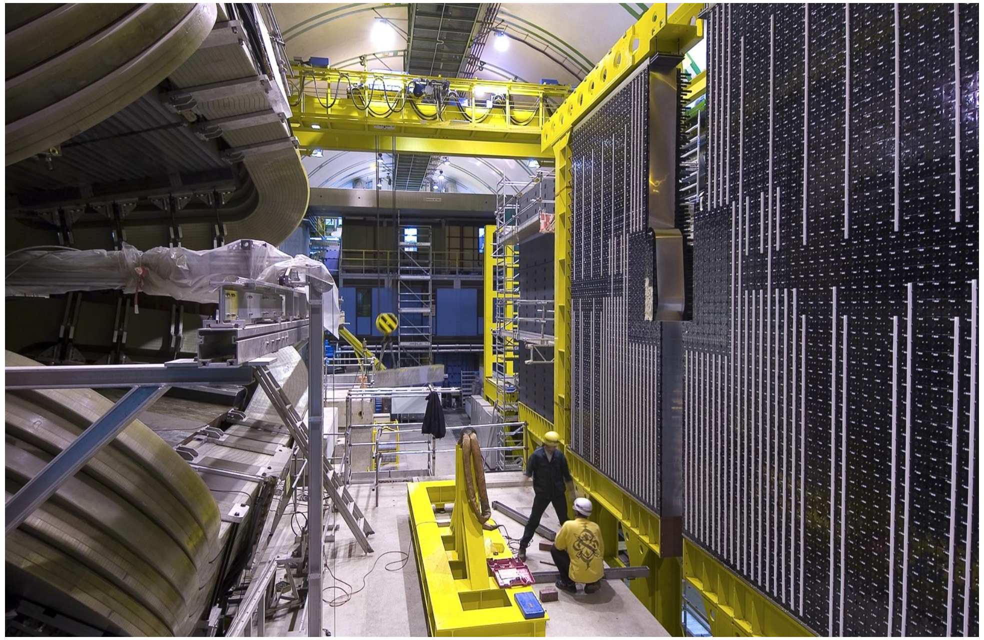
Conclusion

- New results in radiative b-hadron decays at LHCb presented:
- Search for $B_s^0 \to \mu^+\mu^-\gamma$
  - Set limits of branching fractions per bin of di-muon q^2
- Amplitude analysis of $B_s^0 \to K^+K^-\gamma$
  - Analysis of the di-kaon structure up to $m_{KK} < 2400\ \mathrm{MeV/c^2}$
  - First observation of $B_s^0 \to f_2'(1525)\gamma$
  - Measurement of the overall tensor contribution
- Amplitude analysis of $\Lambda_b^0 \to pK^-\gamma$
  - Analysis of the proton-kaon structure up to $m_{pK} < 2500\ \mathrm{MeV/c^2}$
  - First observation of this mode
  - Helpful to the interpretation of measurements in $\Lambda_b^0 \to pK^-l^+l^-$ and potentially to measurements of photon polarization involving analysis of polarized Λ_b^0
  - Helpful to low energy QCD

Backup

Introduction: LHCb

- Coverage in pseudorapidity range $2 < \eta < 5$
- Excellent vertexing and tracking performance
- Ring-imaging Cherenkov detectors
- Calorimeter system
  - $\frac{\sigma_E}{E} = \left(1 + \frac{10}{PT[GeV/c]}\right)\%$
- Hardware Trigger
  - Using Calorimeter and muon systems
- 2-stages Software Trigger
  - Using full event reconstruction
- Collected 3fb^{-1} during the run 1 period at 7 and 8 TeV center of mass energy and 6fb^{-1} during the run 2 period at 13TeV center of mass energy

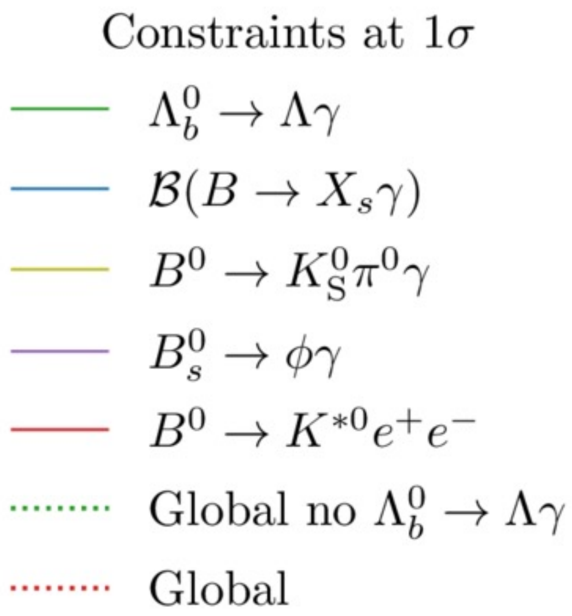


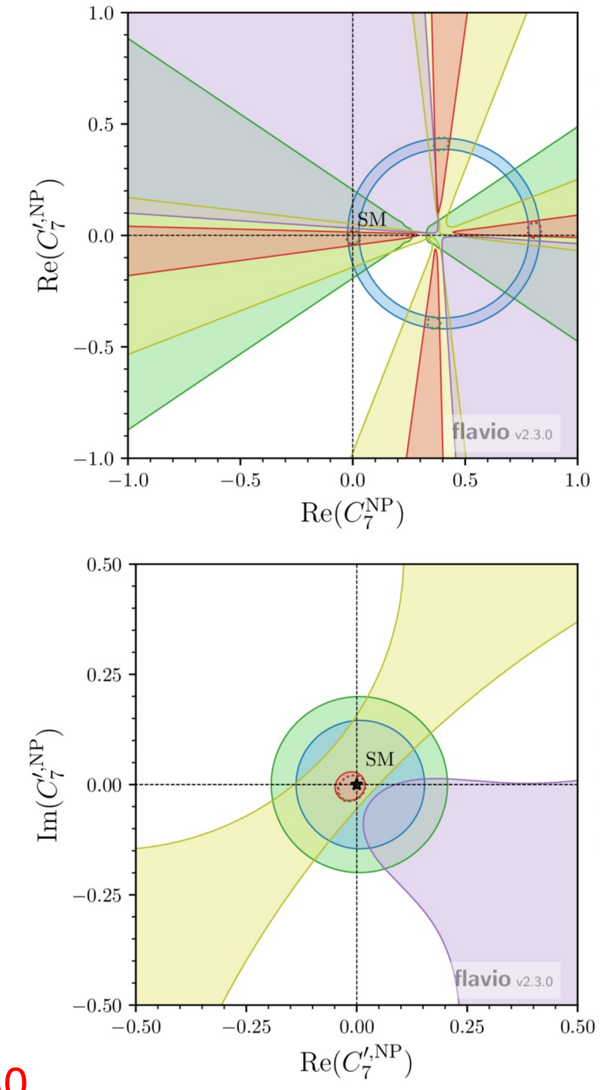
Simulation

Simulation is used to optimise the selection strategy, to estimate the background and signal shapes, and to calculate the efficiencies. The *pp* collisions are generated using PYTHIA [29] with a specific LHCb configuration [30]. Decays of unstable particles are described by EVTGEN [31], in which final-state radiation is generated using PHOTOS [32]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [33] as described in Ref. [34]. The theory model for the signal simulation is computed in Ref. [16].

Introduction

LHCb + B-factories





LHCb-PAPER-2021-030

$B_s^0 \to \mu^+\mu^-\gamma$

$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 4.2 \times 10^{-8}, \ m(\mu^+\mu^-) \in [2m_\mu, \ 1.70]\,\mathrm{GeV}/c^2,$

$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 7.7 \times 10^{-8}, \ m(\mu^+\mu^-) \in [1.70, \ 2.88]\,\mathrm{GeV}/c^2,$

$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 4.2 \times 10^{-8}, \ m(\mu^+\mu^-) \in [3.92, \ m_{B_s^0}]\,\mathrm{GeV}/c^2,$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{I,\ with}\ \phi\ \mathrm{veto}} < 2.9\,(3.4) \times 10^{-8},$$

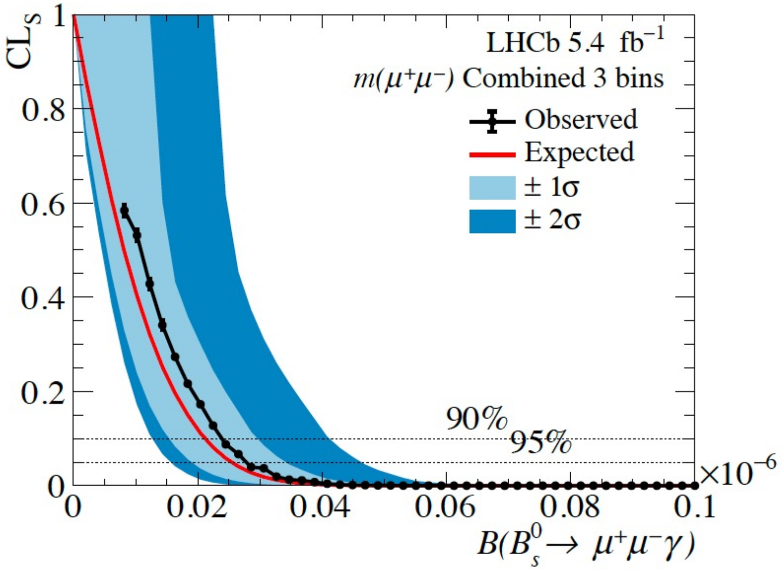
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{comb.}} < 2.5\,(2.8) \times 10^{-8},$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{Bin\ I}} < 3.60(4.22) \times 10^{-8}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{Bin\ II}} < 6.52(7.73) \times 10^{-8}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{Bin\ III}} < 3.44(4.24) \times 10^{-8}$$

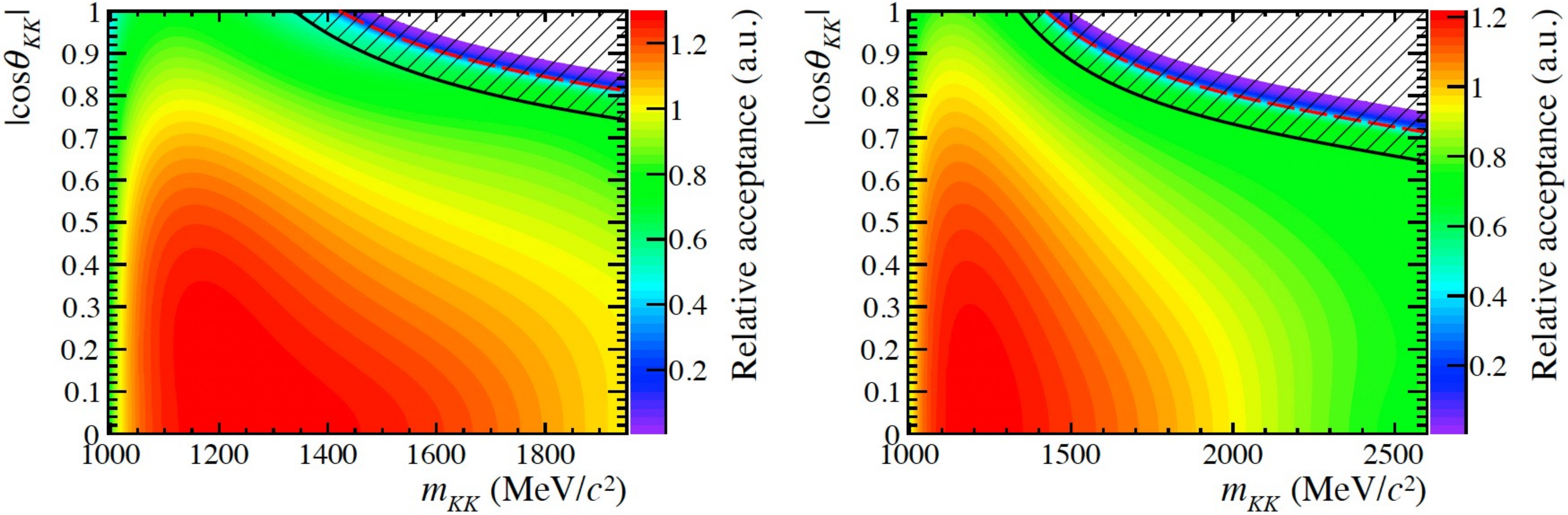
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{Bin\ I}\ \phi\ \mathrm{veto}} < 2.86(3.43) \times 10^{-8}$$



q^2 bin	I	II	III
q^2 [GeV^2/c^4]	$[4m_\mu^2, 2.89]$	$[2.89, 8.29]$	$[15.37, m_{B_s^0}^2]$
$m(\mu^+\mu^-)$ [GeV/c^2]	$[2m_\mu, 1.70]$	$[1.70, 2.88]$	$[3.92, m_{B_s^0}]$
$10^{10} \times \mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)$	82 ± 15	2.54 ± 0.34	9.1 ± 1.1
Fraction of $B_s^0 \to \mu^+\mu^-\gamma$	87%	2.7%	9.8%

ϕ veto $m(\mu^+\mu^-) \in [989.6, \ 1073.4]\,\mathrm{MeV}/c^2.$

$B_s^0 \to K^+K^-\gamma$



$B_s^0 \to K^+K^-\gamma$

$$\mu_{f_2'(1525)} = 1521.8 \pm 1.7 \text{ (stat.) } ^{+1.4}_{-1.9} \text{ (syst.) MeV}/c^2,$$
$$\Gamma_{f_2'(1525)} = 79.3 \pm 3.5 \text{ (stat.) } ^{+3.3}_{-1.5} \text{ (syst.) MeV},$$

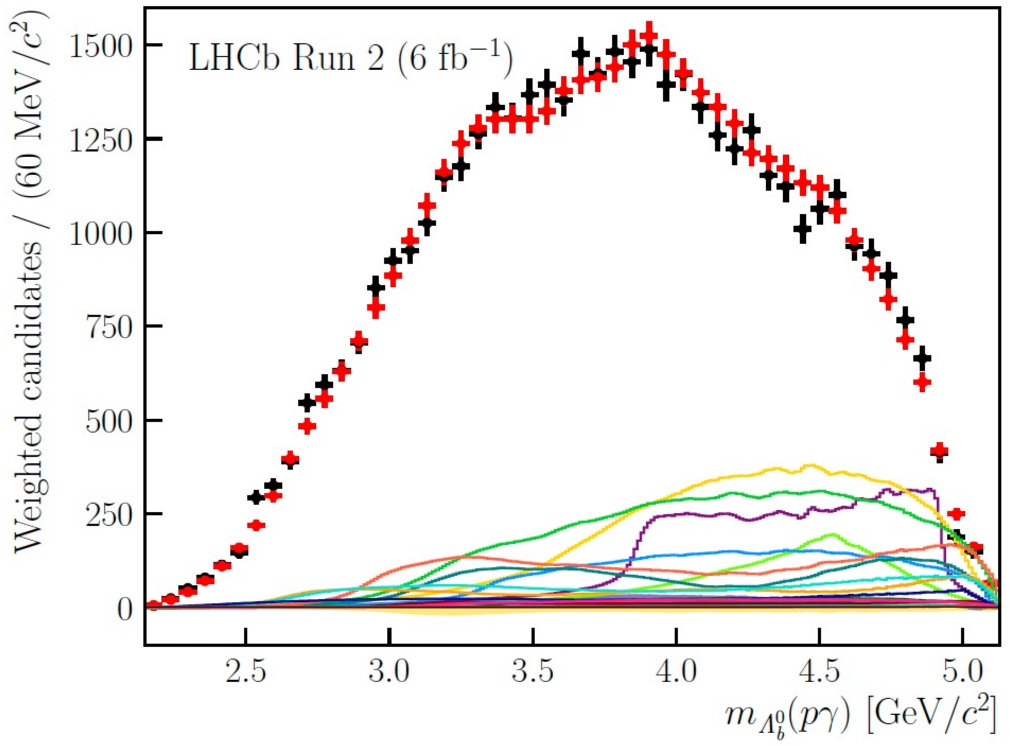
$$\mu_{\phi(1020)} = 1019.50 \pm 0.02 \text{ (stat.)} \pm 0.02 \text{ (syst.) MeV}/c^2,$$
$$\Gamma_{\phi(1020)} = 4.36 \pm 0.05 \text{ (stat.) } ^{+0.03}_{-0.10} \text{ (syst.) MeV},$$

$$r_\phi = 1.0 \pm 0.2 \text{ (stat.)} \pm 0.1 \text{ (syst.)} \quad (\text{GeV}/c)^{-1}.$$

$\Lambda_b^0 \to pK^-\gamma$

$$\mathrm{FF}(n) = \frac{\int_{\mathcal{D}} \left(\frac{\mathrm{d}\Gamma(n)}{\mathrm{d}\mathcal{D}}\right) \mathrm{d}\mathcal{D}}{\int_{\mathcal{D}} \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}\mathcal{D}}\right) \mathrm{d}\mathcal{D}}$$

- $\mathcal{A}(\Lambda, \lambda_\Lambda, \lambda_p, \lambda_\gamma) \propto \overbrace{d^{J_\Lambda}_{\lambda_p \lambda_\Lambda}(\theta_p)}^{\text{Wigner d matrix}} \times \sum_{L,S} \left[\overbrace{C_1^{\Lambda\gamma} C_2^{\Lambda\gamma} C_1^{pK^-} C_2^{pK^-}}^{\text{Clebsch-Gordans}} \overbrace{A_{LS}}^{\text{couplings}} \overbrace{\left(\frac{p}{M_{\Lambda_b^0}}\right)^L \left(\frac{p}{M_{\Lambda_b^0}}\right)^l}^{\text{orb.ang. mom.barriers}} \overbrace{B_L(p) B_l(q)}^{\text{Blat-Weiskopf form factors}} \overbrace{BW(m_{pK})}^{\text{lineshape}} \right]$



Resonance	J^P	m_0	Γ_0	Δm_0	$\Delta\Gamma_0$	σ_{m_0}	σ_{Γ_0}	l	L
$\Lambda(1405)$	$1/2^-$	1405	50.5	±1.3	±2	1.3	2	0	0, 1
$\Lambda(1520)$	$3/2^-$	1519	16	1518 – 1520	15 – 17	1	1	2	0, 1, 2
$\Lambda(1600)$	$1/2^+$	1600	200	1570 – 1630	150 – 250	30	50	1	0, 1
$\Lambda(1670)$	$1/2^-$	1674	30	1670 – 1678	25 – 35	4	5	0	0, 1
$\Lambda(1690)$	$3/2^-$	1690	70	1685 – 1695	50 – 70	5	10	2	0, 1, 2
$\Lambda(1800)$	$1/2^-$	1800	200	1750 – 1850	150 – 250	50	50	0	0, 1
$\Lambda(1810)$	$1/2^+$	1790	110	1740 – 1840	50 – 170	50	60	1	0, 1
$\Lambda(1820)$	$5/2^+$	1820	80	1815 – 1825	70 – 90	5	10	3	1, 2, 3
$\Lambda(1830)$	$5/2^-$	1825	90	1820 – 1830	60 – 120	5	30	2	1, 2, 3
$\Lambda(1890)$	$3/2^+$	1890	120	1870 – 1910	80 – 160	20	40	1	0, 1, 2
$\Lambda(2100)$	$7/2^-$	2100	200	2090 – 2110	100 – 250	10	100	4	2, 3, 4
$\Lambda(2110)$	$5/2^+$	2090	250	2050 – 2130	200 – 300	40	50	3	1, 2, 3
$\Lambda(2350)$	$9/2^+$	2350	150	2340 – 2370	100 – 250	20	100	5	3, 4, 5