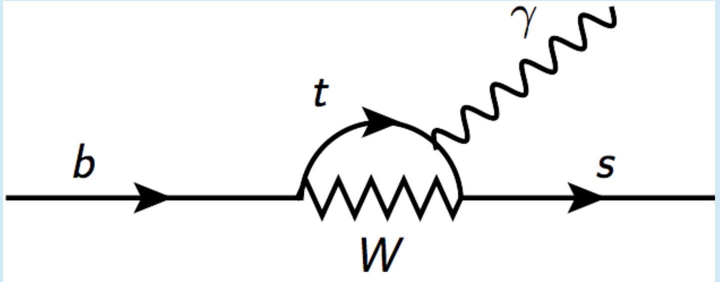
Radiative b-hadron decays at LHCb

Yingrui Hou (LPCA, CNRS)
On behalf of the LHCb collaboration

22nd Conference on Flavor Physics and CP Violation (FPCP 2024)
Chulalongkorn University, 27th-31st May 2024

Radiative b-hadron decays

- On the theory side
  - FCNC is strongly suppressed by the Standard Model (SM)
  - Sensitive to indirect effects of New Physics (NP)
  - Access to test couplings to 3rd generation quarks



- On the measurement side
  - Search for the unobserved decays

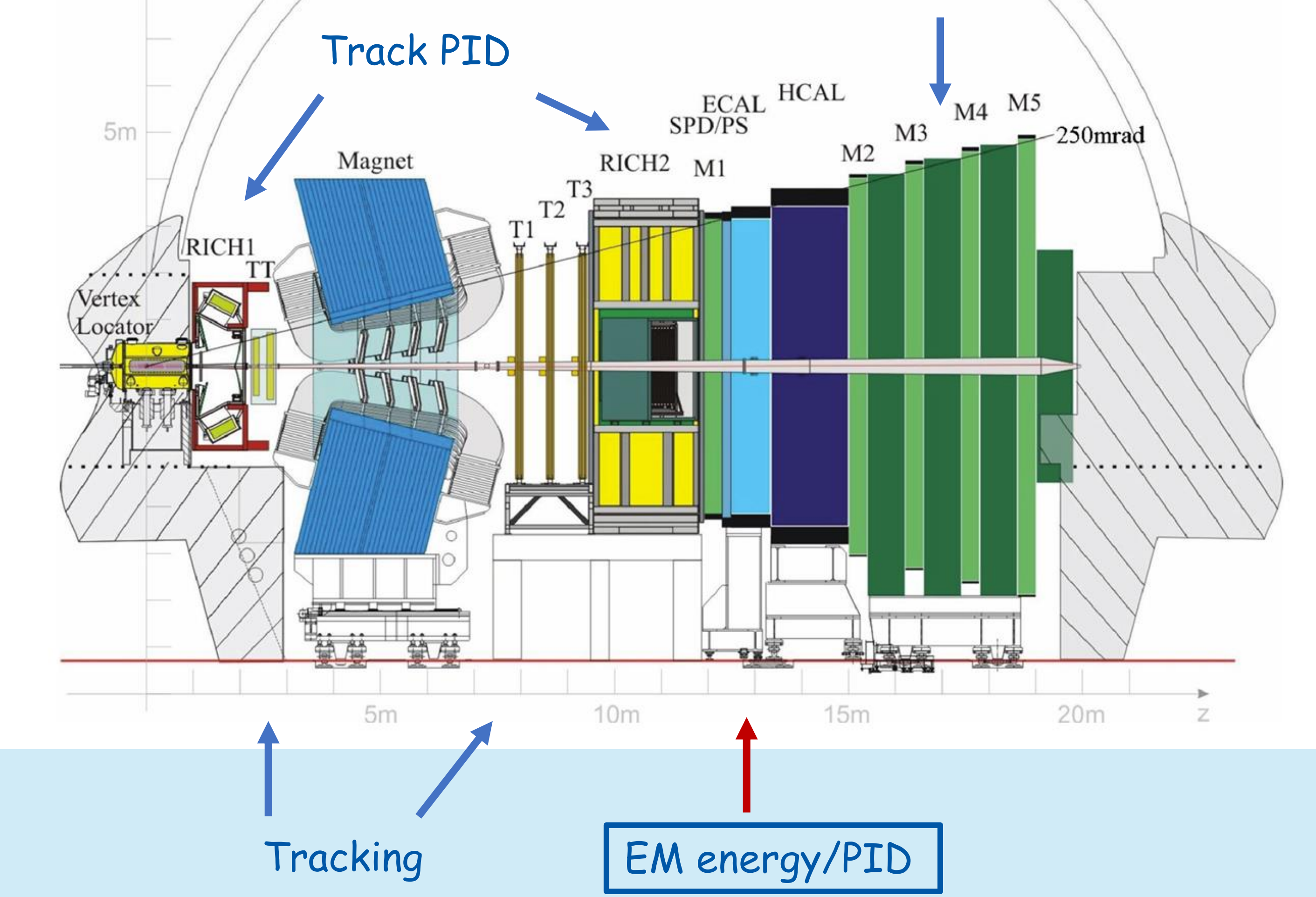
    -> *measurement of branching fraction/upper limit*
  - Amplitude study for the multibody decays

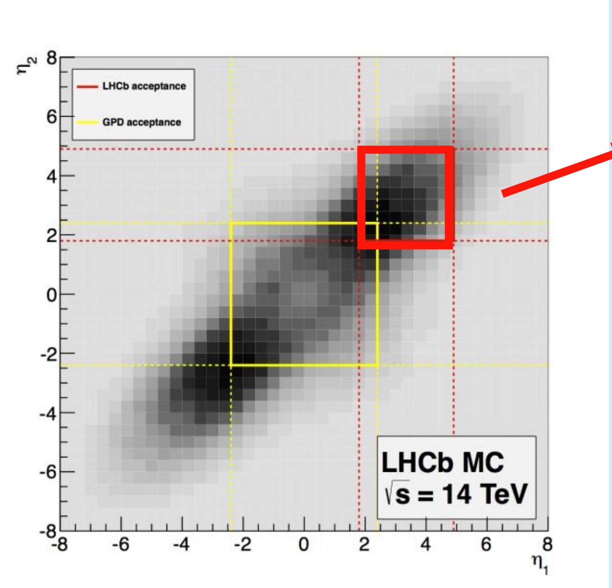
    -> *hadron spectrum at photon pole*

    -> *photon polarisation*

LHCb: A flavour physics detector with high luminosity

Int. J. Mod. Phys. A30, 1530022(2015)
CERN-LHCC-2003-030





LHCb: 27% of b or $\bar{b}$

* $\sigma_{b\bar{b}}$
$= 72\ \mu\mathrm{b}\ (7\ \mathrm{TeV})$
$= 154\ \mu\mathrm{b}\ (13\ \mathrm{TeV})$

*PRL118(2017)052002

- Forward spectrometer, focusing on $b\bar{b}$ production
- Performance
  - $\epsilon_{tracking} \sim 96\%$
  - ECAL resolution: $1\% + \frac{10\%}{\sqrt{E(\mathrm{GeV})}}$

Searching for the unobserved decays

$B_s^0 \rightarrow \mu^+\mu^-\gamma$: arxiv.2404.03375

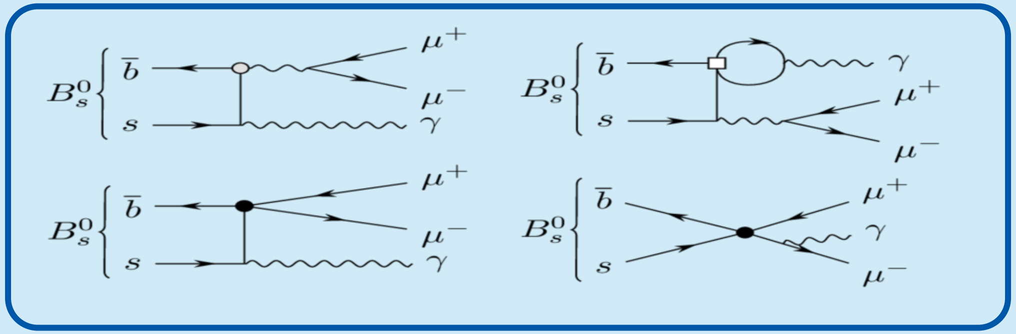
Searching for $B_s^0 \to \mu^+\mu^-\gamma$ decay

arxiv.2404.03375

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

☺ Sensitive to a different set of Wilson coefficients: (C_7, C_9, C_{10}) vs (C_S, C_P, C_{10})
The photon lifts the helicity suppression making $Br(B_s^0 \to \mu^+\mu^-) \sim Br(B_s^0 \to \mu^+\mu^-\gamma)$

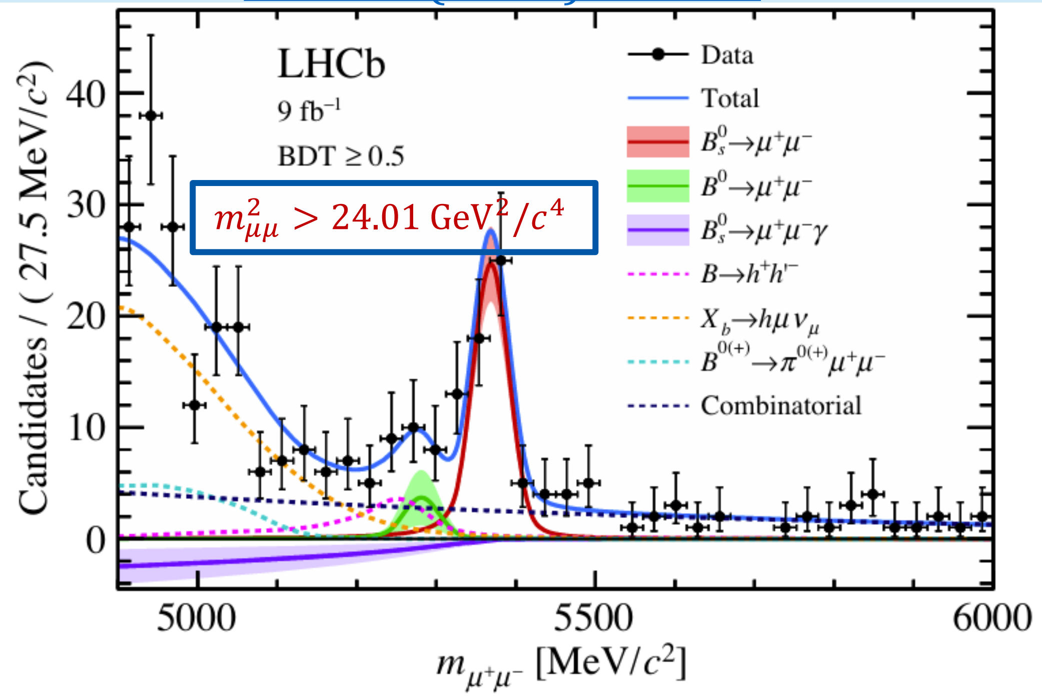
☹ Larger theoretical uncertainties -> $B_s^0 \to \gamma$ form factor
Worse mass resolution due to the photon reconstruction



Theory prediction [JHEP 11(2017) 184]

- $q^2 < 8.64\ \mathrm{GeV}^2/c^4$:
  $Br(B_s^0 \to \mu^+\mu^-\gamma) = (8.3 \pm 1.3) \times 10^{-9}$
- $q^2 > 15.84\ \mathrm{GeV}^2/c^4$:
  $Br(B_s^0 \to \mu^+\mu^-\gamma) = (8.9 \pm 1.0) \times 10^{-9}$

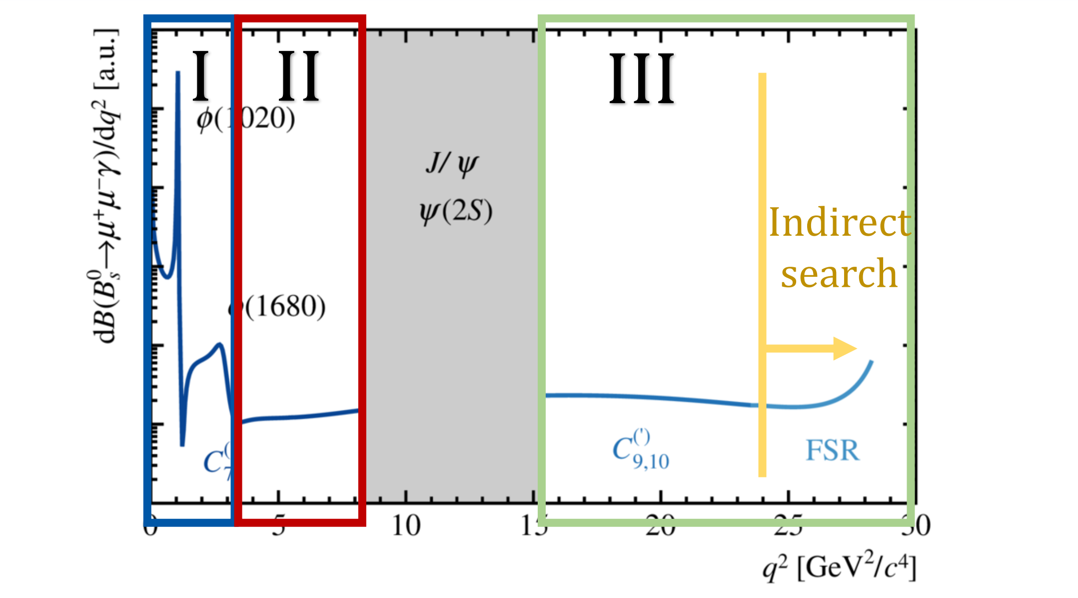
PRL128(2022)041801



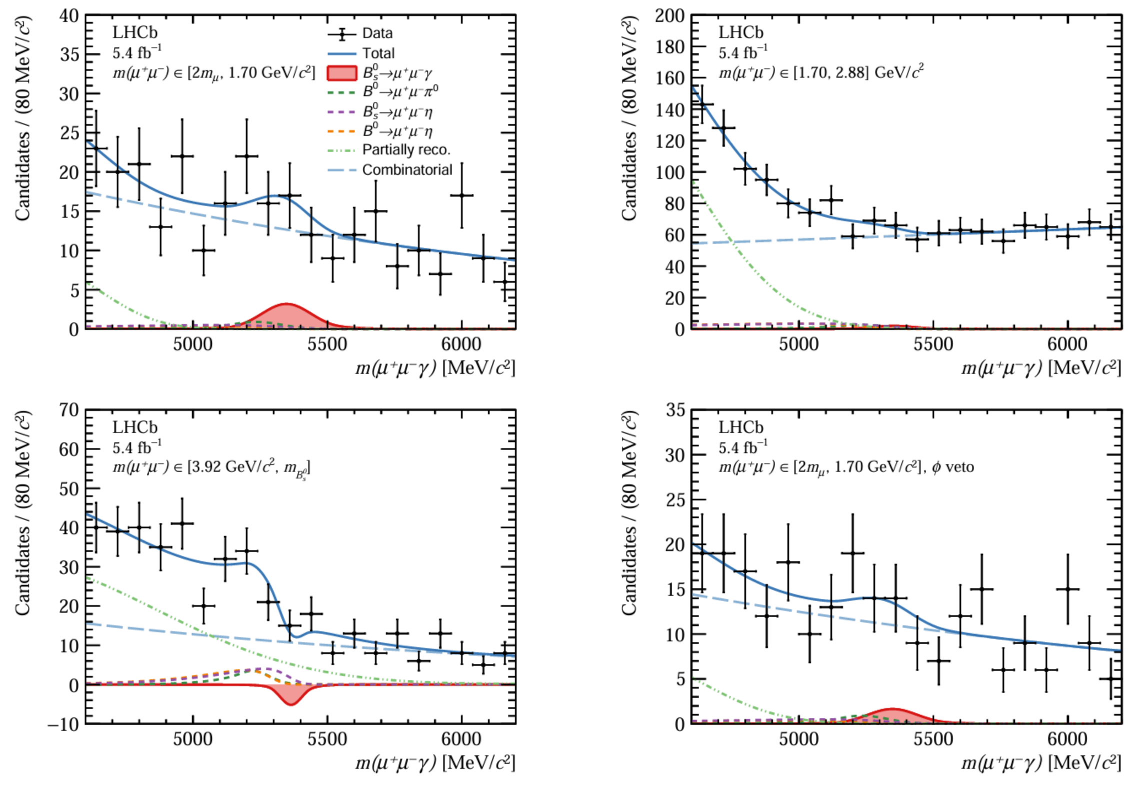
Searching for $B_s^0 \to \mu^+\mu^-\gamma$ decay

arxiv.2404.03375

- Strategy
  - 2016-2018 data (5.4fb^{-1})
  - Searching in 3 q^2 regions (ϕ-vetoed bin I is also studied)
  - Control channel: $B_s^0 \to \phi(KK)\gamma$
    - Check the agreement between data and simulation
  - Normalisation channel: $B_s^0 \to J/\psi(\mu\mu)\eta(\gamma\gamma)$
    - High statistics + Similar final state to the signal



Mass fit of $B_s^0 \to \mu\mu\gamma$ in all q^2 regions

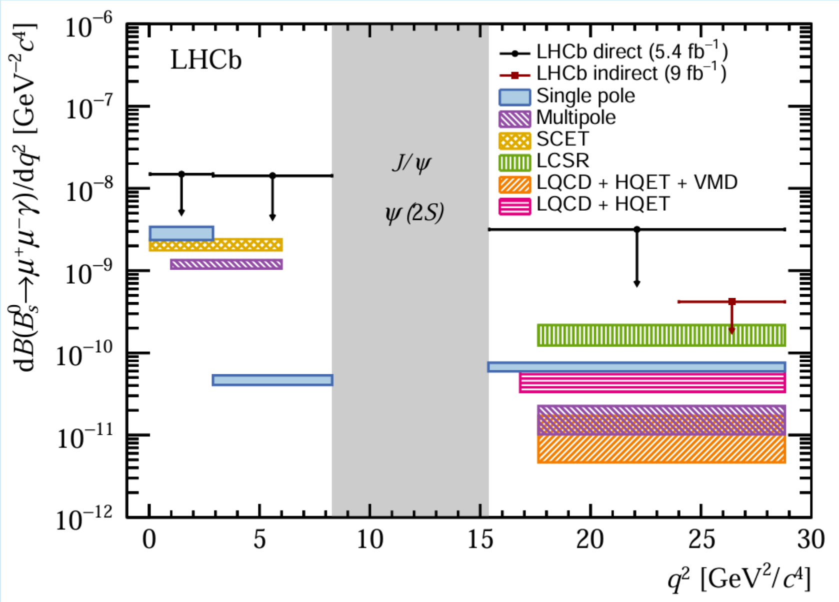


Searching for $B_s^0 \to \mu^+\mu^-\gamma$ decay

arxiv.2404.03375

- Results
  - First direct search of $B_s^0 \to \mu\mu\gamma$ at low q^2
  - No statistically significant signal is observed in all q^2 regions
- Constrain in the theoretical context
  - Indirect method reaches lower ULs
  - Direct search is more sensitive to the full q^2 spectrum
    - New constrains in the low q^2 region
- Run3 data will improve the sensitivity of the search

$$
\begin{aligned}
\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{I}} &< 3.6\,(4.2) \times 10^{-8}, \\
\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{II}} &< 6.5\,(7.7) \times 10^{-8}, \\
\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{III}} &< 3.4\,(4.2) \times 10^{-8}, \\
\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{I,\ with\ }\phi\mathrm{\ veto}} &< 2.9\,(3.4) \times 10^{-8}, \\
\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{comb.}} &< 2.5\,(2.8) \times 10^{-8},
\end{aligned}
$$



Amplitude analyses of the multibody decays

$\Lambda_b \to pK^-\gamma$: arxiv.2403.03710

$B_s^0 \to KK\gamma$: LHCb-paper-2024-002 (in preparation)

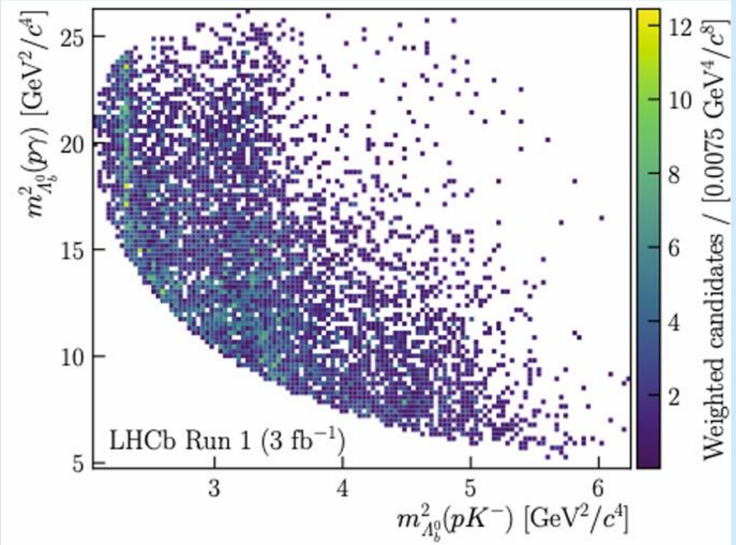
Amplitude analysis of $\Lambda_b \to pK^-\gamma$

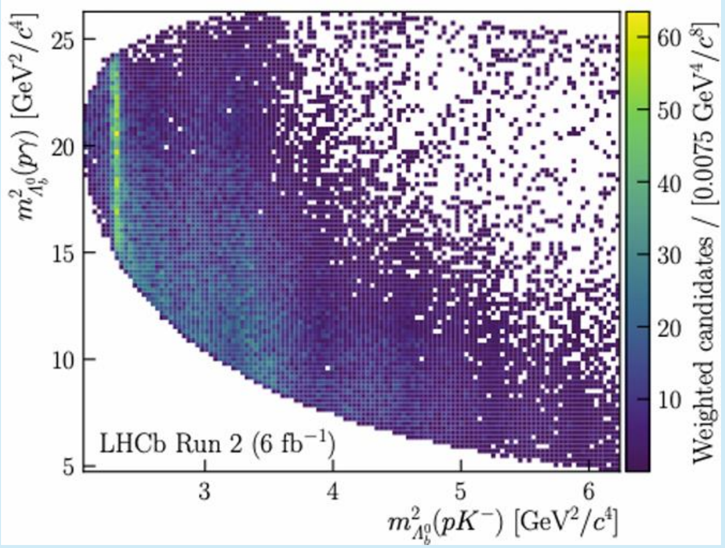
arxiv.2403.03710

- The $\Lambda_b \to pK\gamma$ provides information about the composition of the pK^-spectrum with unique access to the heavier Λ states.
  - Could constitute useful input to future measurements of photon polarization in $b \to s\gamma$
  - Vital input to low energy-QCD (light baryon) theory
- Strategy
  - Using full Run1 and Run2 data
  - Building amplitude model with helicity formalism
  - Performing unbinned maximum likelihood fit to the Dalitz plane $(m_{pk}^2, m_{p\gamma}^2)$

$$d^{J_\Lambda}_{\lambda_p \lambda_\Lambda}(\theta_p) \times \sum_{L=|J_{\Lambda_b^0}-S|}^{|J_{\Lambda_b^0}+S|} \sum_{S=|J_\Lambda - J_\gamma|}^{|J_\Lambda + J_\gamma|} \left[C_1 C_2 C_3 \; h^\Lambda_{LS} \left(\frac{p}{M_{\Lambda_b^0}}\right)^L \left(\frac{q}{M_\Lambda}\right)^l B_L(p) B_l(q) \mathrm{BW}_l(m_{pK}) \right]$$

connect p and Λ^* helicity frames; Wigner d; Clebsch-Gordans; fit parameter, LS coupling; orb. ang. mom. barriers; line shape with form factors

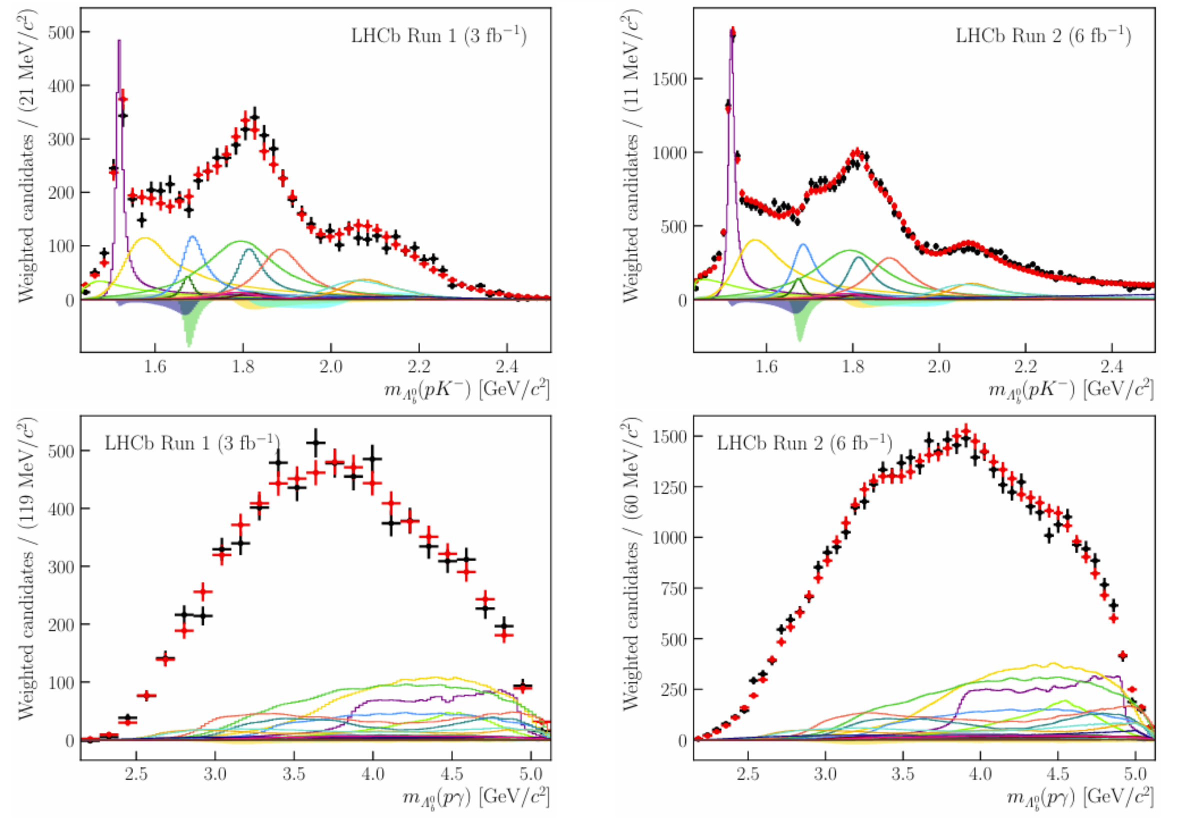


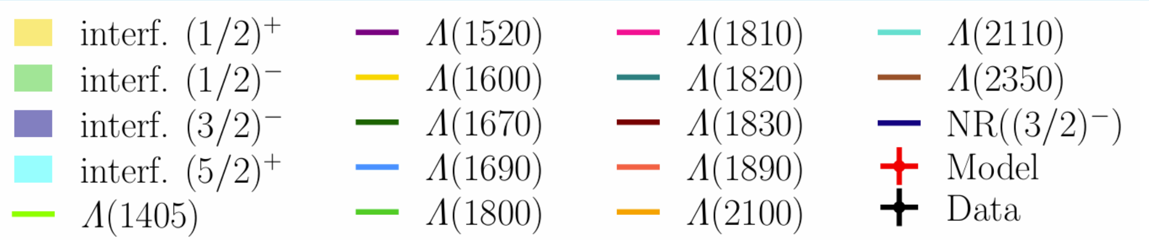


Amplitude analysis of $\Lambda_b \to pK^-\gamma$

arxiv.2403.03710

- The default fit model
  - All known Λ states + a nonresonant contribution ($J^P = \frac{3}{2}^-$)



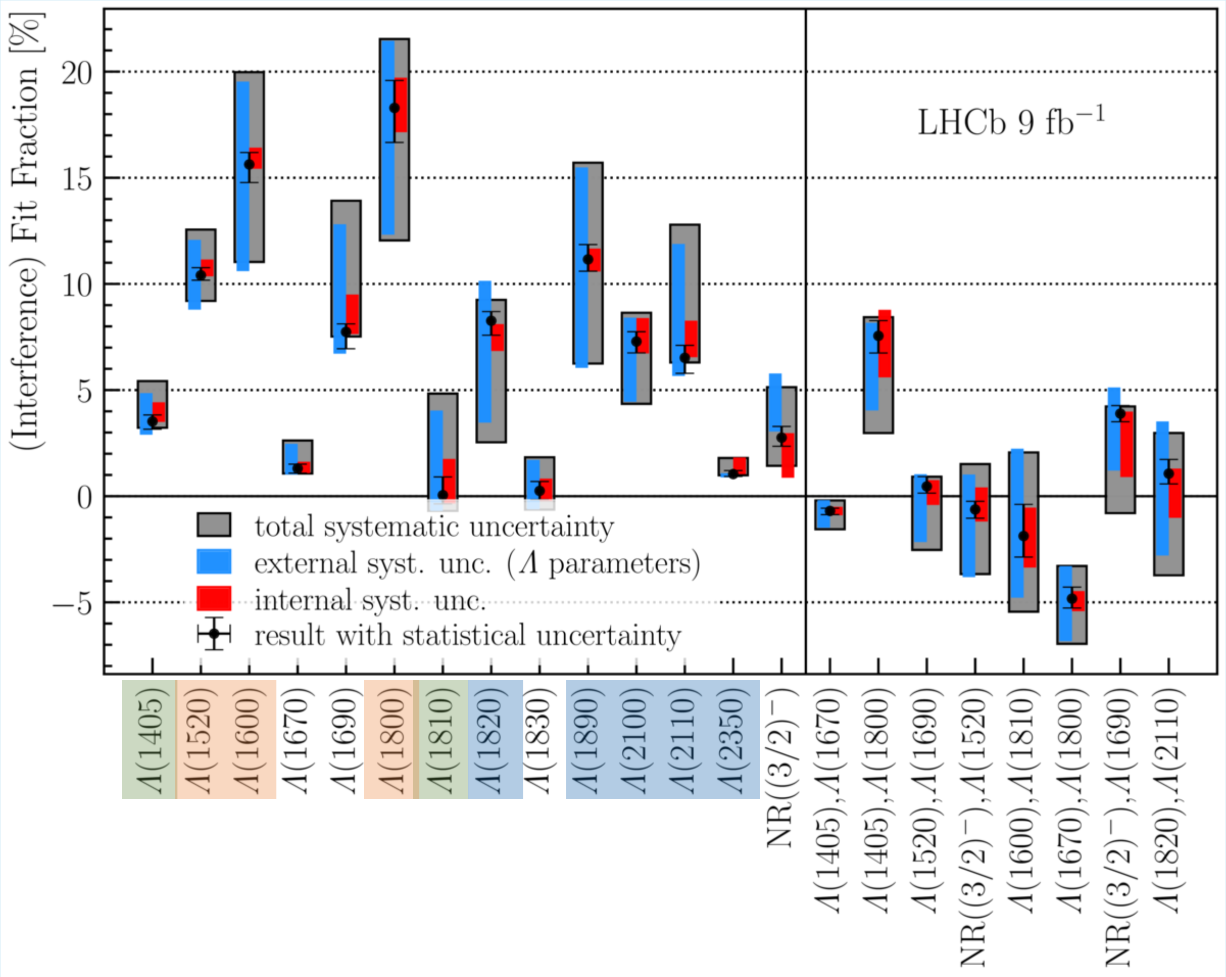


- The uncertainties
  - Resonance parameters (external input)
    - Dominant uncertainty
  - Statistics
  - Model-related systematic uncertainties
    - Model choice and mass resolution
  - Other uncertainties
    - Mass fit, acceptance model, background estimation

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

arxiv.2403.03710

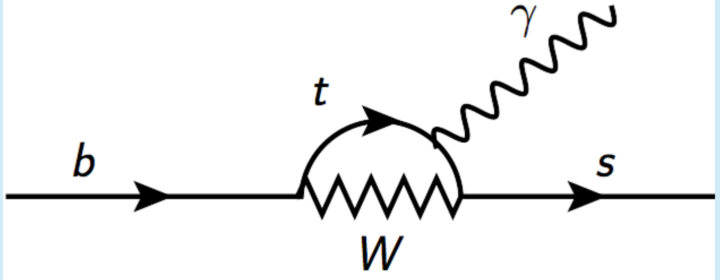
- Results are given in terms of fit and interference fractions
- The largest resonant contributions are $\Lambda(1800), \Lambda(1600), \Lambda(1890)$ and $\Lambda(1520)$
- Compared to $\Lambda_b \to J/\psi pK$
  - Contributions of $\Lambda(1405)$, $\Lambda(1810)$ are smaller, while contribution of $\Lambda(1820)$ is larger
  - Heavy resonances $\Lambda(1890)$, $\Lambda(2100)$, $\Lambda(2110)$ and $\Lambda(2350)$ are larger in the radiative case
- Future measurements and data will improve the precision

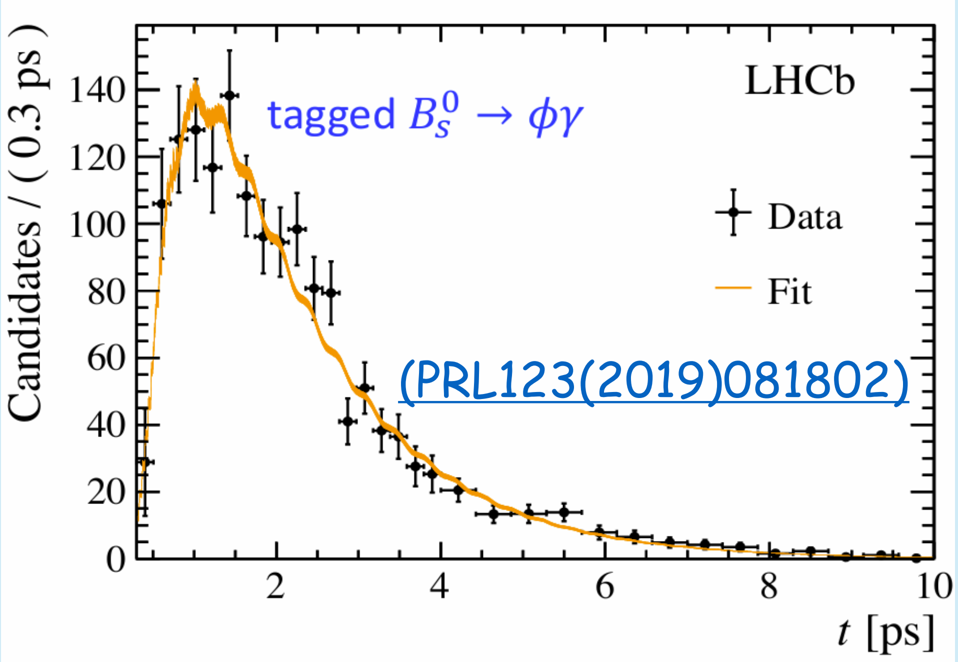


Amplitude analysis of $B_s^0 \to KK\gamma$

LHCb-paper-2024-002

- One of the golden channels of $b \to s\gamma$ transition
  - Dominated by a virtual intermediate top quark coupled to a W boson
  - Photon polarisation in $B_s^0 \to \phi\gamma$ has been measured by LHCb
    - $\sim 1.5 - 2\sigma$ compatibility with the SM
    - Possible new radiative decay modes with KK resonance?
- Strategy
  - Full Run1 and Run2 data
  - Building amplitude with isobar model in the folded helicity semi-plane $(m_{KK}, |\cos\theta_{KK}|)$
    - Decay rate asymmetry of B_s is neglected
    - Mass resolution is included





(PRL123(2019)081802)

Amplitude analysis of $B_s^0 \to KK\gamma$

LHCb-paper-2024-002

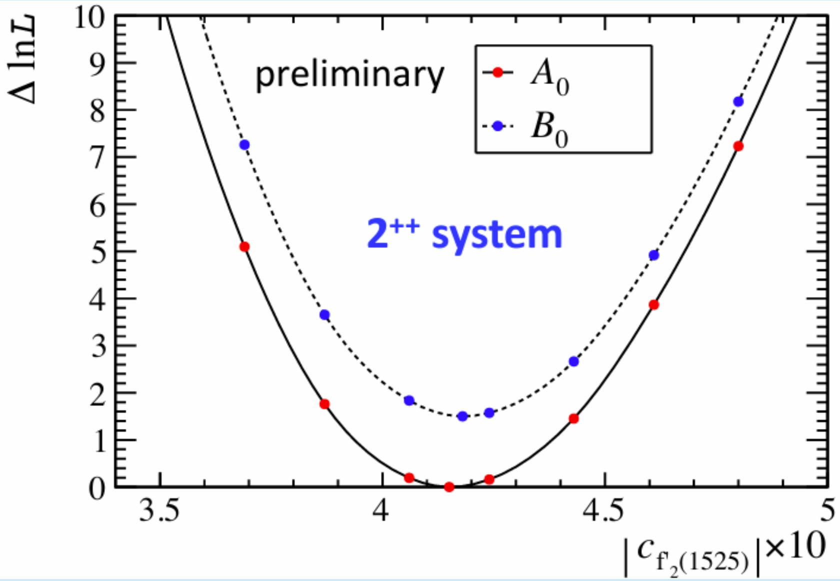
- KK states are well-established with large $\Delta\ln L$ gain and isobar significance
- Nonresonant state: P-wave (1^{--}), uniformly in mass with constant phase
- Several distinct tensor states give similar significances.

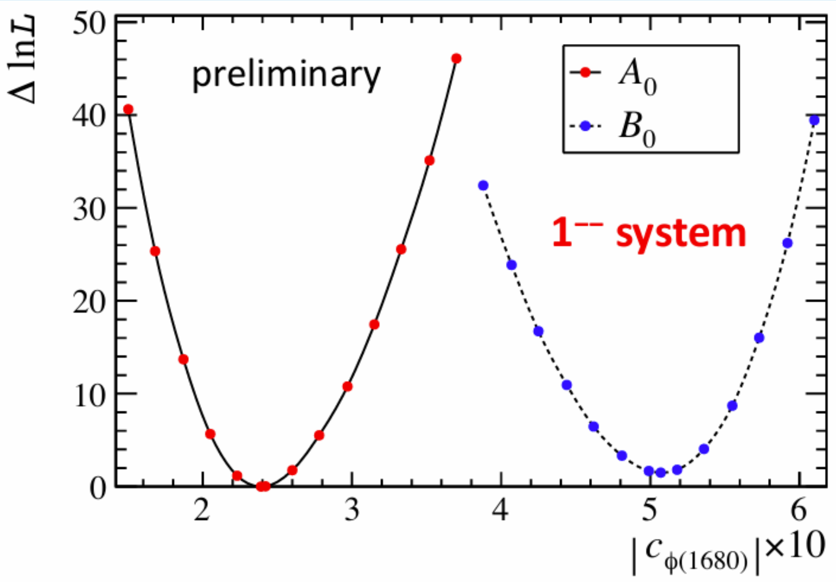
State	J^{PC}	μ_R (MeV/c^2)	Γ_R (MeV)	$\mathcal{B}_{K^+K^-}$ (%)	$\lvert c_R \rvert$ (×10)	($\chi^2_{\lvert c_R \rvert}$)	$\Delta\ln\mathcal{L}$
$\phi(1020)$	1^{--}	1019.461 ± 0.016	4.249 ± 0.013	49.2 ± 0.5	10 (fix)	-	-
$f_2'(1525)$	2^{++}	1517.4 ± 2.5	86 ± 5	43.8 ± 1.1	4.16 ± 0.09	(2270)	-
$\phi(1680)$	1^{--}	1689 ± 12 (*)	211 ± 24 (*)	seen	2.40 ± 0.15	(266)	+304
$f_2(1270)$	2^{++}	1275.5 ± 0.8	$186.6\ ^{+2.2}_{-2.5}$	$2.30\ ^{+0.25}_{-0.20}$	1.07 ± 0.17	(41)	+18
$\phi_3(1850)$	3^{--}	1854 ± 7	$87\ ^{+28}_{-23}$	seen	0.61 ± 0.16	(14)	+15
$f_2(2010)$	2^{++}	$2011\ ^{+62}_{-76}$	$202\ ^{+67}_{-62}$	seen	0.74 ± 0.18	(16)	+13
$(KK)_{NR}$	1^{--}	-			0.79 ± 0.26	(10)	+17

Amplitude analysis of $B_s^0 \to KK\gamma$

LHCb-paper-2024-002

- Several quasi-degenerate solutions with similar ΔLL
  - Weakly constrained interference pattern
  - Preferred solution is with the smallest fit-fractions and constructive interferences of the individual states





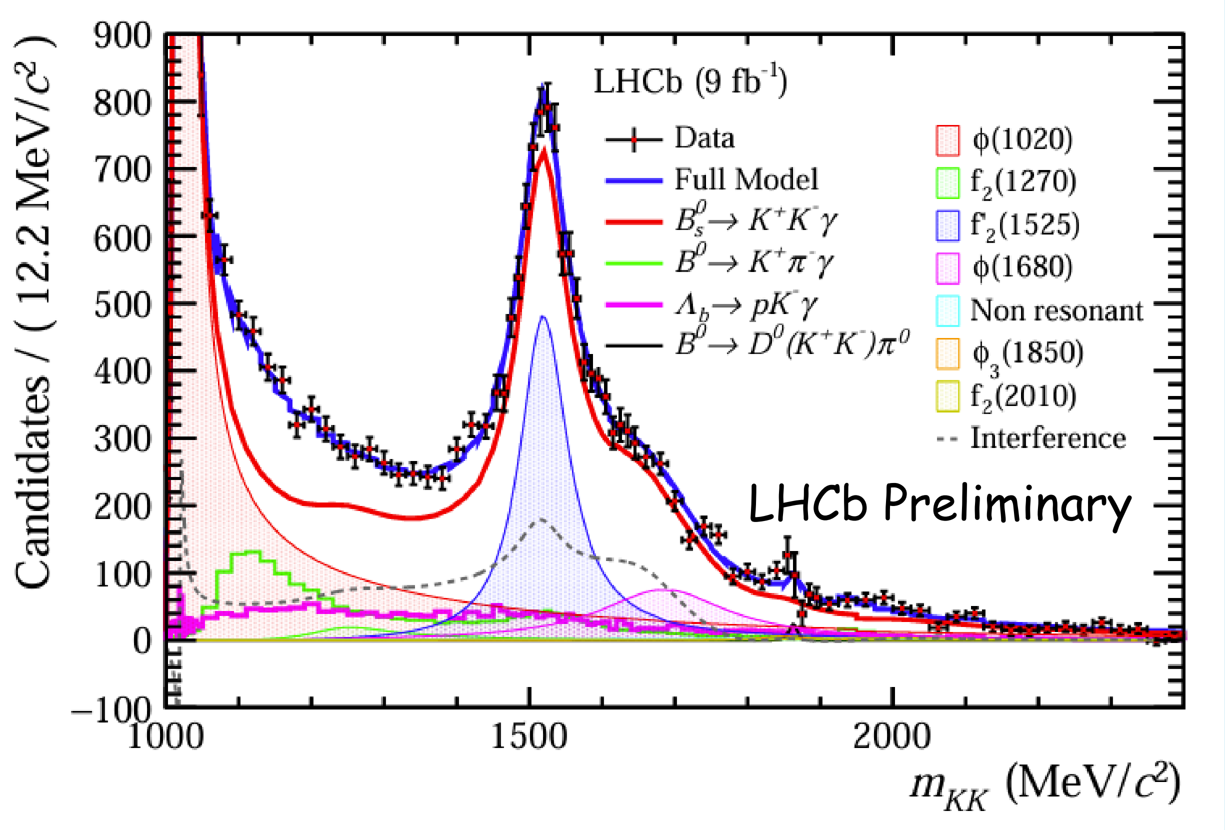
Amplitude analysis of $B_s^0 \to KK\gamma$

LHCb-paper-2024-002

- Best fit
  - Signal yield: $(44.4 \pm 0.5) \times 10^3$
  - The overall tensor states (f_2) fit-fraction is $(16.8 \pm 0.5 \pm 0.7)\%$
  - A new radiative decay is observed for the first time

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

  - Mass and width of $f_2'(1525)$ are measured in good agreement with current world average and measurements



Conclusions

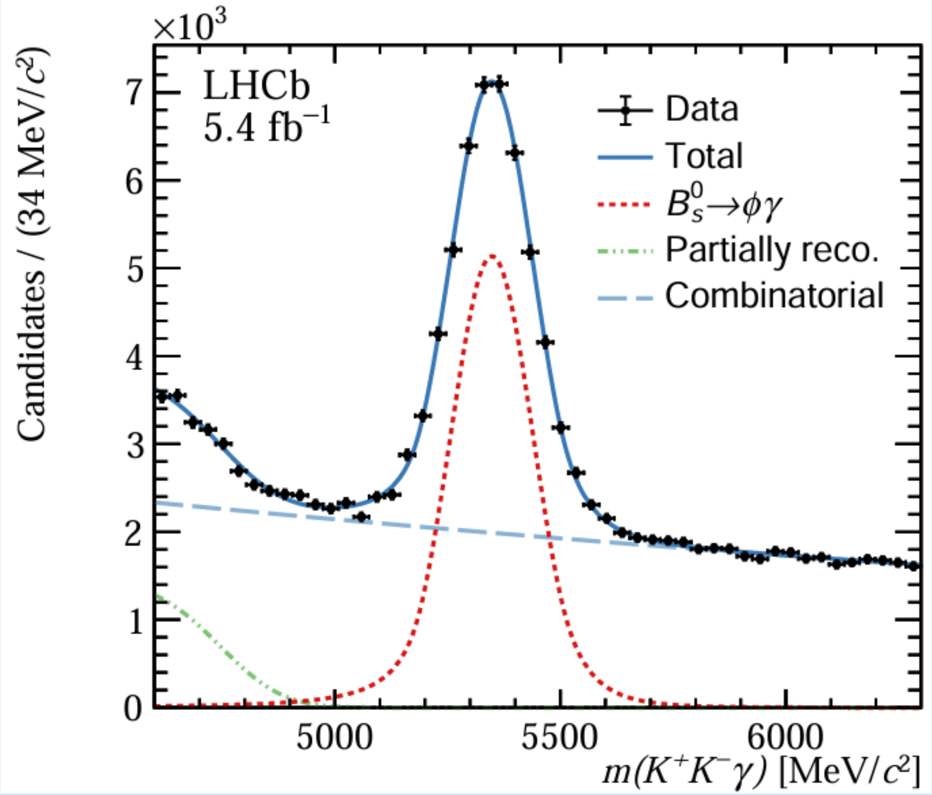
- New results from LHCb
  - First direct search of $B_s \to \mu^+\mu^-\gamma$ (ULs in low q^2 region)
  - Amplitudes of $\Lambda_b \to pK^-\gamma$ and $B_s \to K^+K^-\gamma$ (new decay observed!)
- The precision and sensitivity of the LHCb radiative decay measurements can be improved with Run3 data and results from other experiments
- More results from Run1 and Run2 data are undergoing
  - CPV and branching fraction measurements, amplitude analyses…

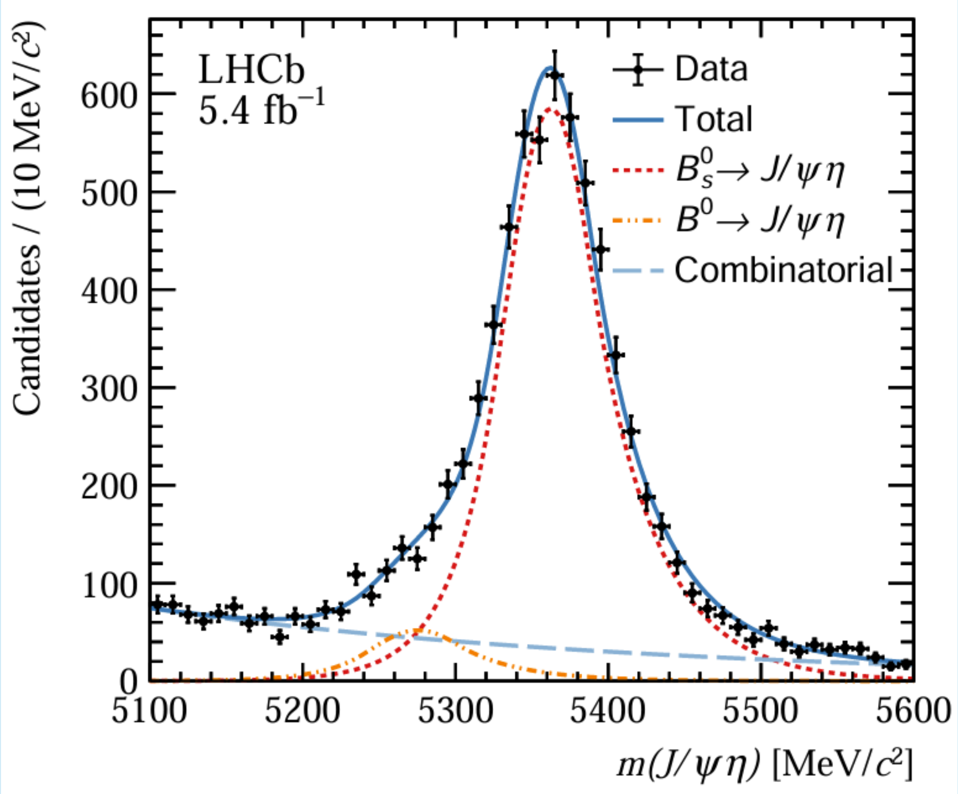
- Stay tuned for the coming results!

BACKUP

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

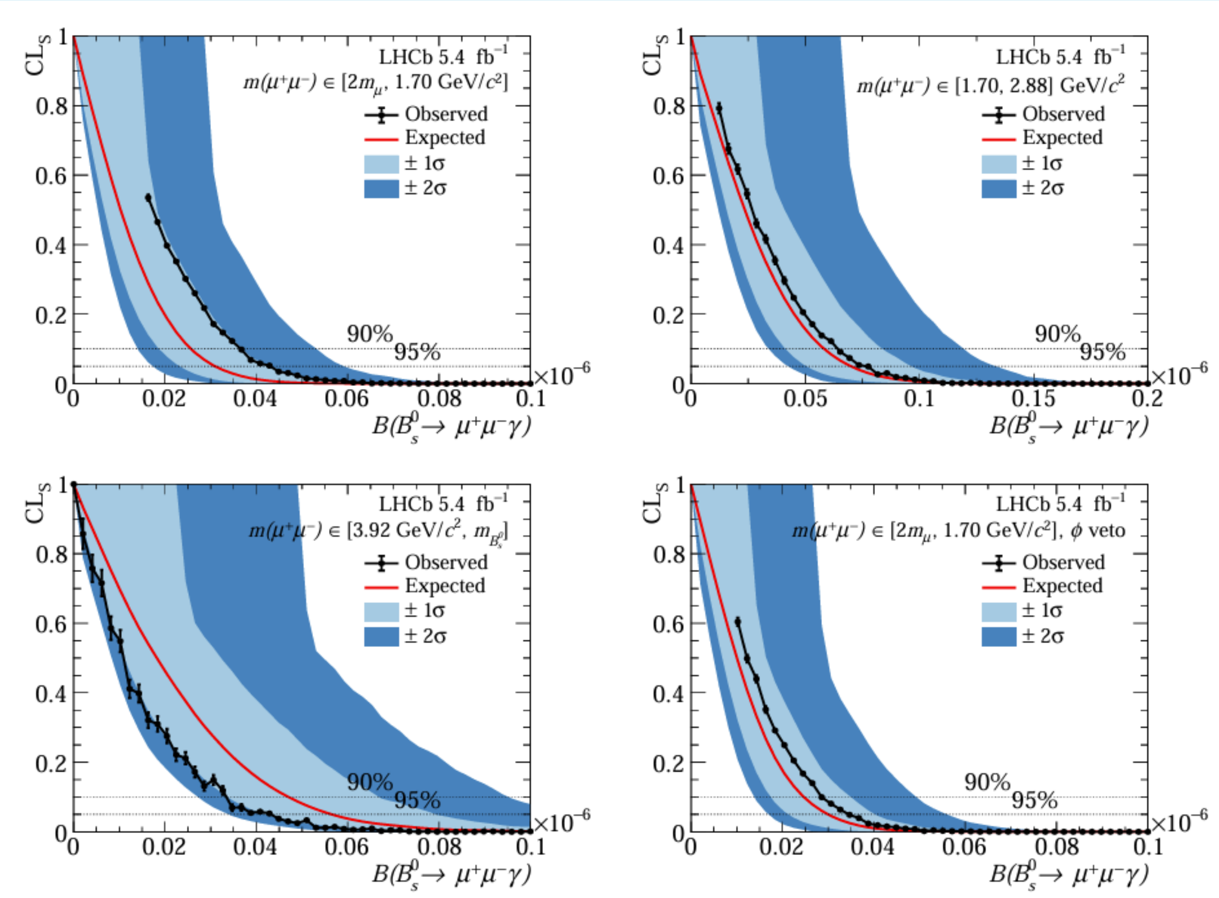
- Mass fit to the control channel and normalization channel data.

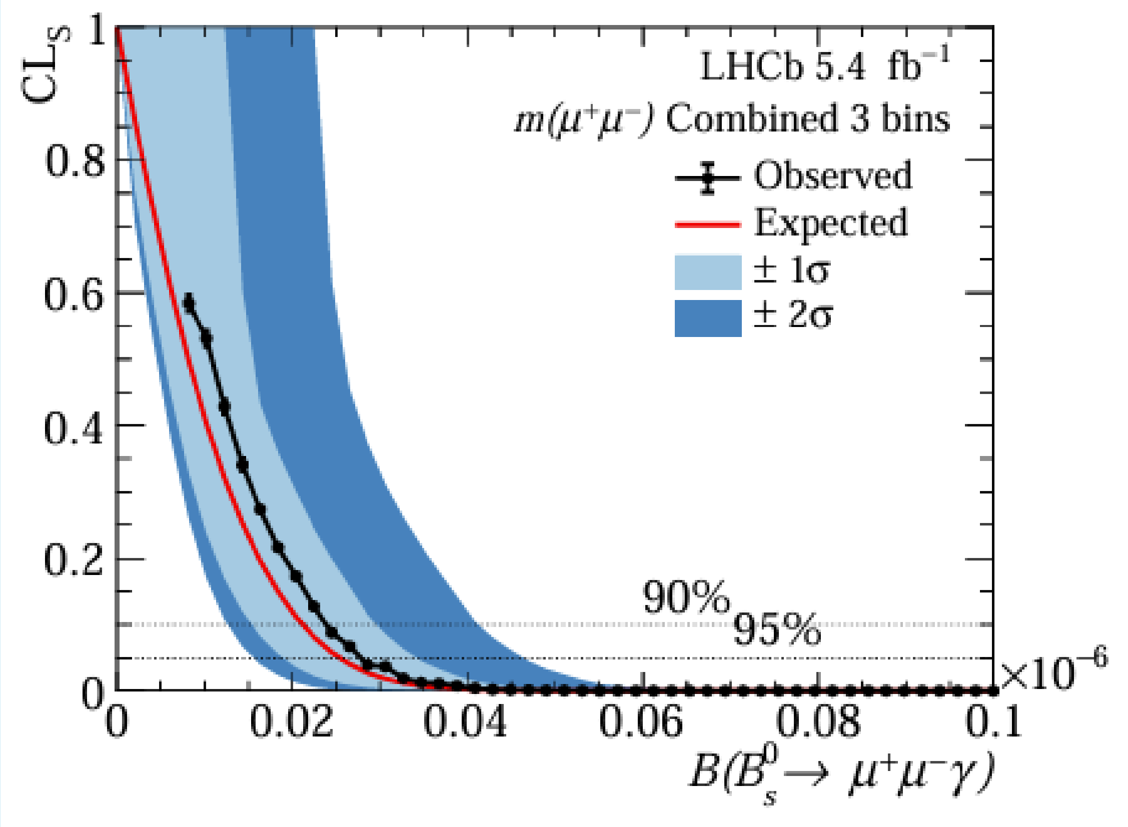




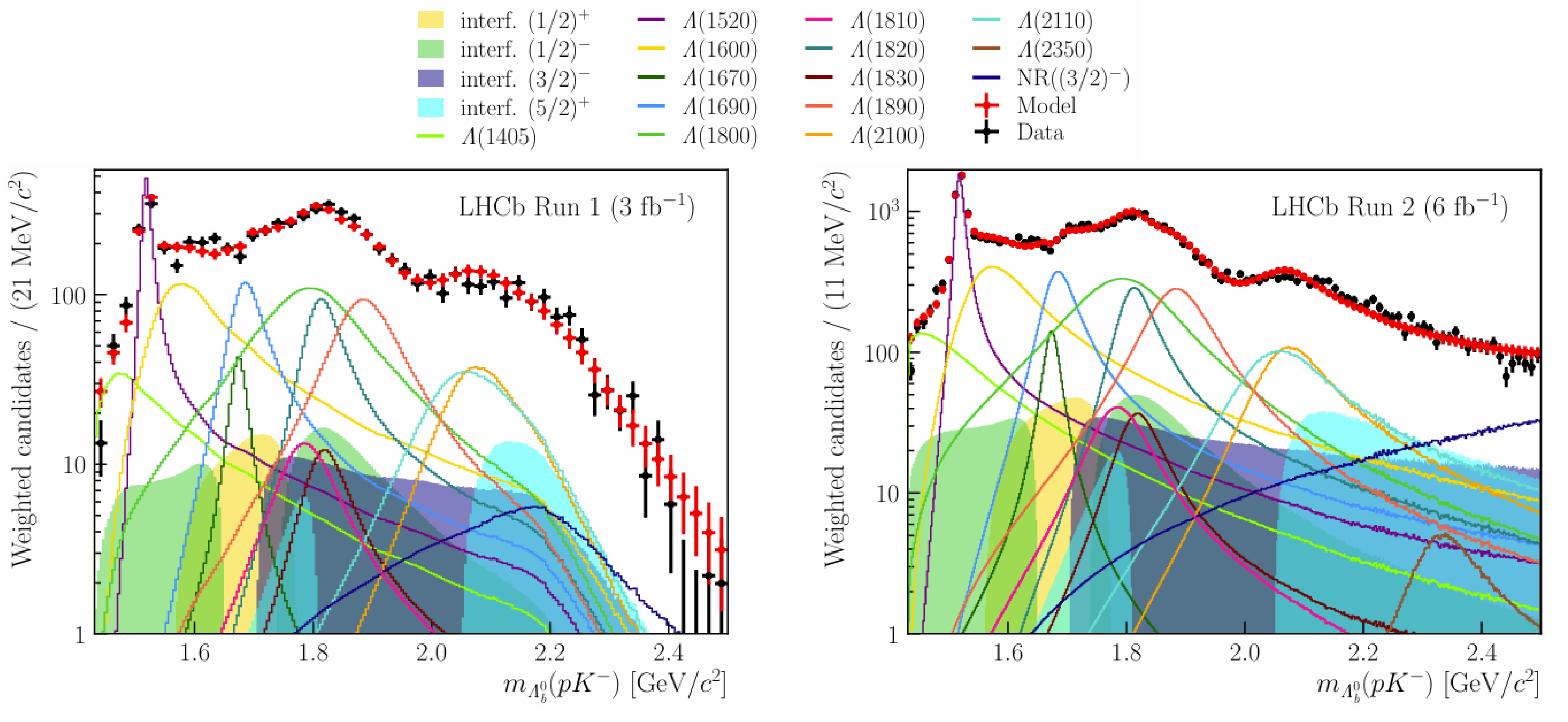
$B_s \to \mu\mu\gamma$

- CL scans in different q^2 regions





$\Lambda_b \to pK\gamma$



$\Lambda_b \to pK\gamma$

- Fit and interference fractions

Observable	Value	σ_{stat}	$\sigma_{\text{syst}}^{\text{internal}}$	$\sigma_{\text{syst}}^{\text{external}}$	σ_{syst}
$\Lambda(1405)$	3.5	$^{+0.3}_{-0.4}$	$^{+0.9}_{-0.0}$	$^{+1.3}_{-0.6}$	$^{+1.9}_{-0.3}$
$\Lambda(1520)$	10.4	$^{+0.4}_{-0.2}$	$^{+0.7}_{-0.0}$	$^{+1.7}_{-1.6}$	$^{+2.2}_{-1.2}$
$\Lambda(1600)$	15.6	$^{+0.6}_{-0.9}$	$^{+0.8}_{-0.2}$	$^{+3.9}_{-5.0}$	$^{+4.3}_{-4.6}$
$\Lambda(1670)$	1.3	$^{+0.2}_{-0.2}$	$^{+0.3}_{-0.2}$	$^{+1.2}_{-0.3}$	$^{+1.3}_{-0.2}$
$\Lambda(1690)$	7.7	$^{+0.4}_{-0.8}$	$^{+1.8}_{-0.1}$	$^{+5.1}_{-1.0}$	$^{+6.2}_{-0.2}$
$\Lambda(1800)$	18.3	$^{+1.3}_{-1.6}$	$^{+1.4}_{-1.1}$	$^{+3.2}_{-6.0}$	$^{+3.2}_{-6.2}$
$\Lambda(1810)$	0.1	$^{+0.9}_{-0.4}$	$^{+1.7}_{-0.4}$	$^{+4.0}_{-0.7}$	$^{+4.8}_{-0.7}$
$\Lambda(1820)$	8.3	$^{+0.4}_{-0.7}$	$^{-0.2}_{-1.4}$	$^{+1.9}_{-4.8}$	$^{+1.0}_{-5.7}$
$\Lambda(1830)$	0.3	$^{+0.4}_{-0.4}$	$^{+0.6}_{-0.5}$	$^{+1.5}_{-0.9}$	$^{+1.6}_{-0.9}$
$\Lambda(1890)$	11.2	$^{+0.7}_{-0.6}$	$^{+0.5}_{-0.6}$	$^{+4.3}_{-5.1}$	$^{+4.6}_{-4.9}$
$\Lambda(2100)$	7.3	$^{+0.5}_{-0.5}$	$^{+1.1}_{-0.6}$	$^{+1.1}_{-2.8}$	$^{+1.4}_{-2.9}$
$\Lambda(2110)$	6.5	$^{+0.6}_{-0.7}$	$^{+1.7}_{-0.0}$	$^{+5.4}_{-0.9}$	$^{+6.3}_{-0.2}$
$\Lambda(2350)$	1.0	$^{+0.2}_{-0.1}$	$^{+0.8}_{-0.0}$	$^{+0.0}_{-0.2}$	$^{+0.8}_{-0.1}$
$\text{NR}(3/2^-)$	2.8	$^{+0.5}_{-0.4}$	$^{+0.2}_{-1.9}$	$^{+3.0}_{+0.3}$	$^{+2.4}_{-1.3}$

$\Lambda(1405), \Lambda(1670)$	-0.7	$^{+0.1}_{-0.2}$	$^{+0.2}_{-0.2}$	$^{+0.5}_{-0.8}$	$^{+0.5}_{-0.9}$
$\Lambda(1405), \Lambda(1800)$	7.6	$^{+0.7}_{-0.8}$	$^{+1.2}_{-2.0}$	$^{+0.6}_{-3.5}$	$^{+0.9}_{-4.6}$
$\Lambda(1520), \Lambda(1690)$	0.5	$^{+0.5}_{-0.3}$	$^{+0.3}_{-0.9}$	$^{+0.6}_{-2.6}$	$^{+0.5}_{-3.0}$
$\Lambda(1520), \text{NR}(3/2^-)$	-0.6	$^{+0.4}_{-0.4}$	$^{+1.0}_{-0.6}$	$^{+1.6}_{-3.2}$	$^{+2.1}_{-3.0}$
$\Lambda(1600), \Lambda(1810)$	-1.9	$^{+1.5}_{-1.0}$	$^{+1.3}_{-1.5}$	$^{+4.1}_{-2.9}$	$^{+3.9}_{-3.6}$
$\Lambda(1670), \Lambda(1800)$	-4.8	$^{+0.5}_{-0.4}$	$^{+0.4}_{-0.6}$	$^{+1.5}_{-2.0}$	$^{+1.5}_{-2.1}$
$\Lambda(1690), \text{NR}(3/2^-)$	3.9	$^{+0.4}_{-0.4}$	$^{+0.1}_{-3.0}$	$^{+1.2}_{-2.7}$	$^{+0.3}_{-4.7}$
$\Lambda(1820), \Lambda(2110)$	1.1	$^{+0.7}_{-0.5}$	$^{+0.2}_{-2.1}$	$^{+2.5}_{-3.9}$	$^{+1.9}_{-4.8}$