Radiative Rare b-Hadron Decays at LHCb

On behalf of LHCb collaboration

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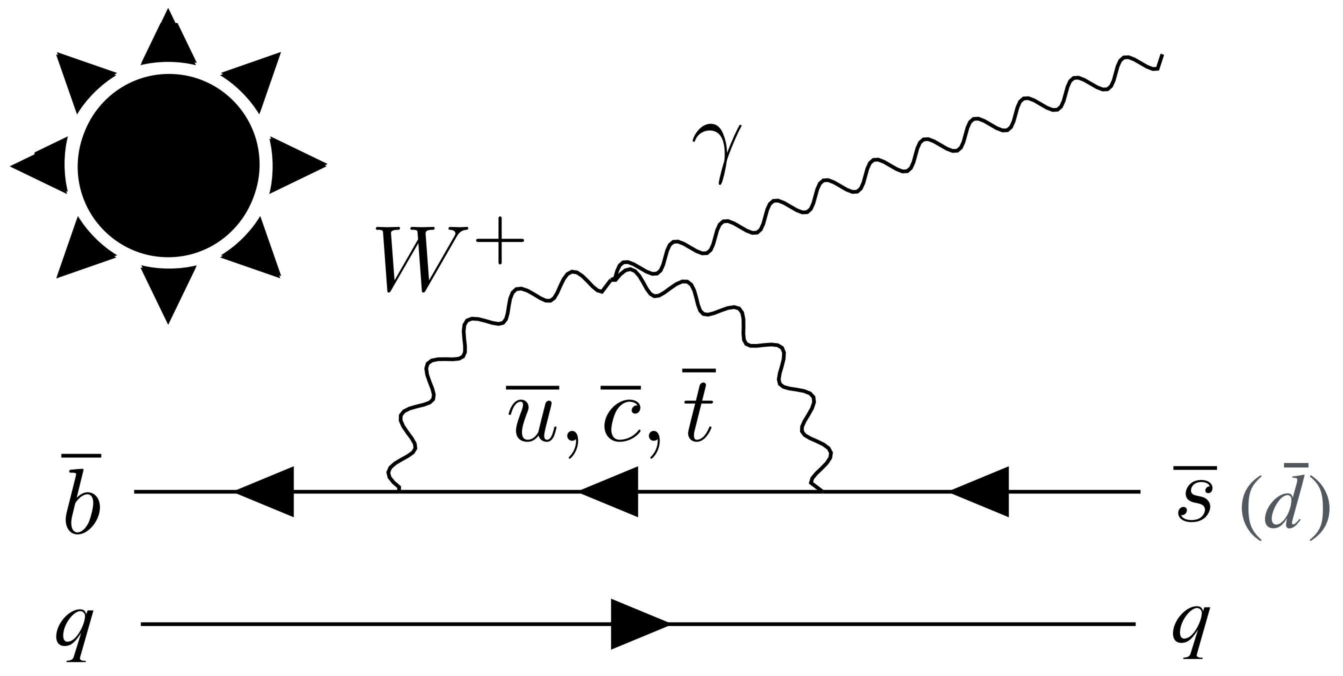
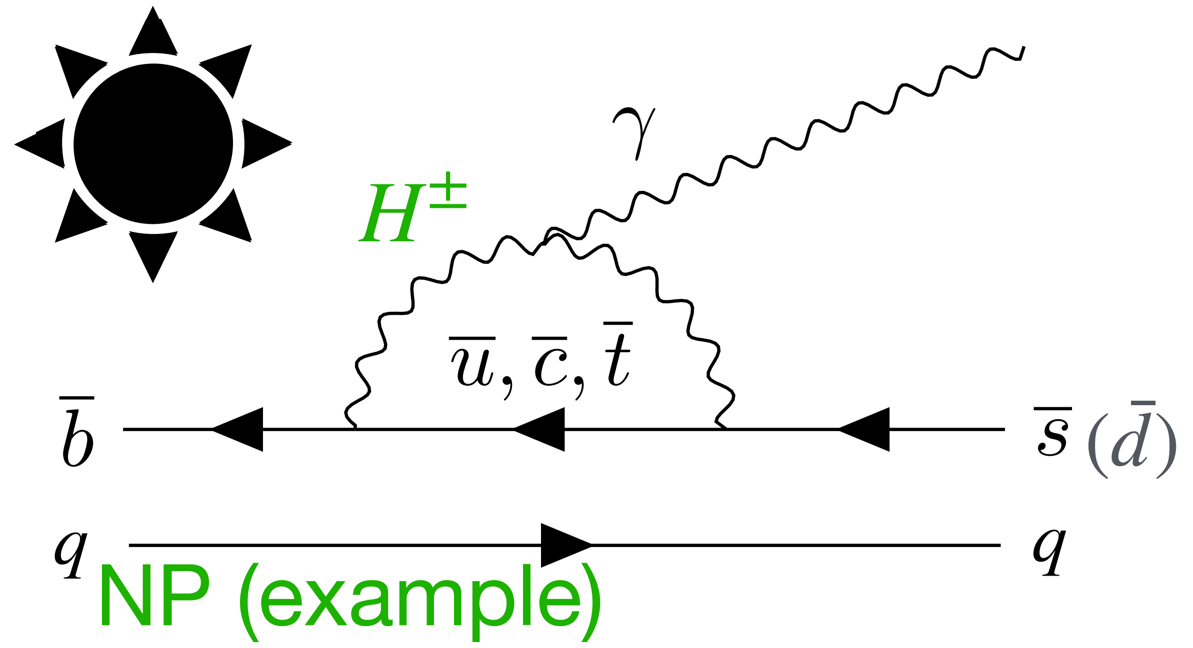
Radiative B-decays

- Flavour Changing Neutral Currents (FCNC): $b \to s(d)\gamma$
  - Proceed at loop-level → suppressed in the SM
  - Low BF's due to CKM suppression
    - Even lower for $b \to d\gamma$ transitions given $|V_{td}/V_{ts}| \sim 0.2$
- Branching ratios (BR) ~ few 10^{-5} for $b \to s\gamma$ transitions, ~10^{-6} for $b \to d\gamma$ ones
- Very sensitive to NP since SM contribution is small!



radiative electroweak decays (SM)



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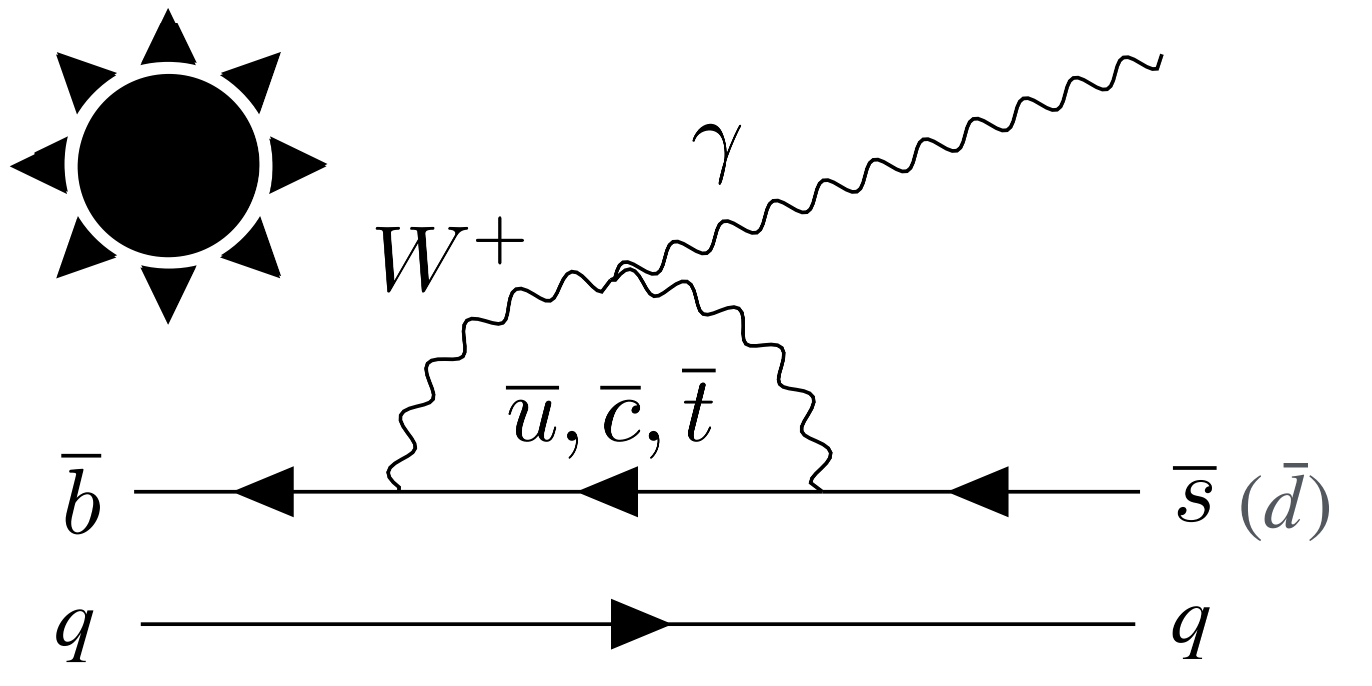


radiative electroweak decays (SM)

Effective hamiltonian described as operator product expansion, C_i being the Wilson coefficients, that encode the short-distance physics, and $\mathcal{O}_i$ the corresponding operators

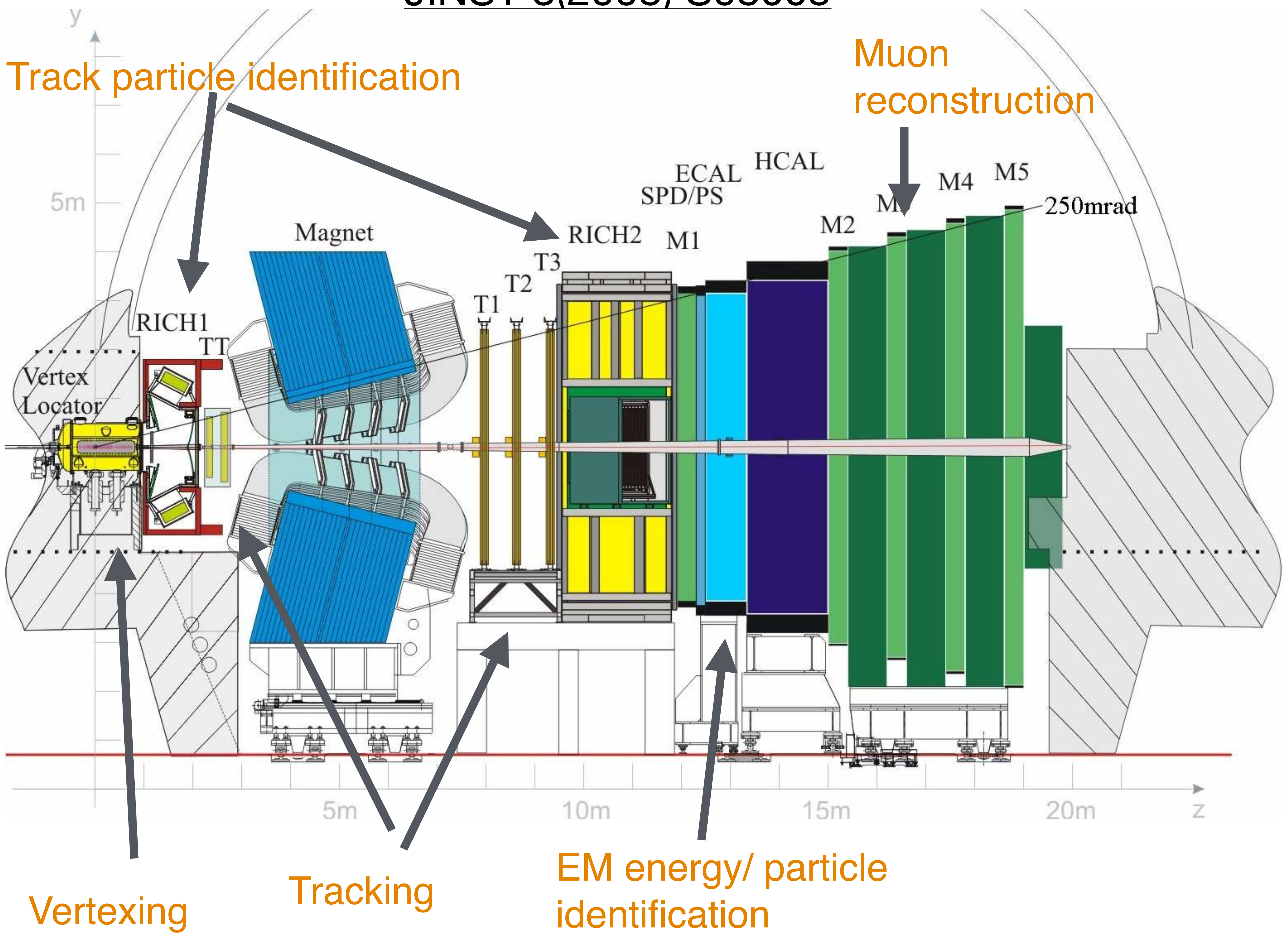
$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i (\underbrace{C_i \mathcal{O}_i}_{\text{Left handed part}} + \underbrace{C_i^{'} \mathcal{O}_i^{'}}_{\text{Right handed part}})$$

$$C_i^{(')} = C_i^{SM} + C_i^{NP}$$

Coupling	Radiative $b \to s\gamma$	Leptonic $B \to \mu\mu$	Semileptonic $b \to s\ell\ell$
$\mathcal{C}_7^{(\prime)}$	✓		✓
$\mathcal{C}_9^{(\prime)}$			✓
$\mathcal{C}_{10}^{(\prime)}$		✓	✓
$\mathcal{C}_S^{(\prime)}$		✓	
$\mathcal{C}_P^{(\prime)}$		✓	

LHCb experiment

JINST 3(2008) S08005



- Designed for the study of b and c hadrons
- Forward arm spectrometer with unique coverage in pseudorapidity ($2 < \eta < 5$)
- Excellent vertex resolution
  - $\sigma_{IP} = 20\ \mu m$
- Excellent momentum resolution
  - $\Delta p/p = 0.5\% - 1.0\,\%\,(5 - 200\ GeV/c)$
- Good photon energy resolution

  $\sigma(E)/E = 1\% + 10\,\%/\sqrt{E}$
- Efficient particle identification
  - $\epsilon(K \to K) \sim 95\,\%$ for $\epsilon(\pi \to K) \sim 5\,\%$
  - $\epsilon(e) \sim 90\,\%$ for $\epsilon(h \to e) \sim 5\,\%$
  - $\epsilon(\mu) \sim 98\,\%$ for $\epsilon(\pi \to \mu) \sim 1 - 3\,\%$

Selected results from radiative decays

$b \to d\gamma$

- Measurement of $B^0 \to \rho^0\gamma$ branching fraction [LHCb-PAPER-2025-017 in preparation]

Preliminary

$b \to s\gamma$

- Constraints on the photon polarisation in $b \to s\gamma$ transitions using $B_s^0 \to \phi e^+e^-$ decays [JHEP 03 (2025) 047]
- Amplitude analysis of the radiative decay $B_s^0 \to K^+K^-\gamma$ [JHEP 08 (2024) 093]

Other recent results not covered today

- Search for $B_s^0 \to \mu^+\mu^-\gamma$ decays [JHEP 07 (2024) 101]
- Amplitude analysis of $\Lambda_b^0 \to pK^-\gamma$ decay [JHEP 06 (2024) 098]

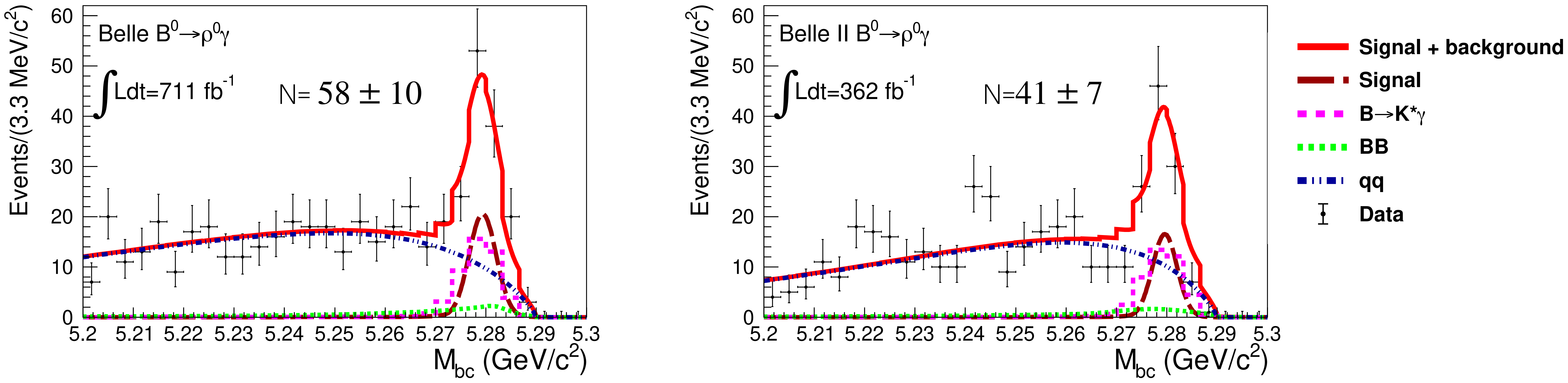
$B^0 \to \rho^0\gamma$ branching fraction

LHCb-PAPER-2025-017
In preparation

Preliminary

- First observed by Belle and BaBar [PRL 101 (2008) 111801, PRD78 (2008)112001]
  - Latest PDG average, combining BaBar and Belle measurements, is $(8.6 \pm 1.5) \times 10^{-7}$ [PDG]
- Recent result combining Belle and Belle II data [PhysRevD.111.L071103]

PhysRevD.111.L071103



- Using Run 1+ 2 LHCb data (9 fb^{-1})
- First measurement associated to the $b \to d\gamma$ transitions in LHCb
  - Measurement of the ratio of the branching fractions between $B^0 \to \rho^0\gamma$ and $B^0 \to K^{*0}\gamma$
    - Provide an independent and direct constraint on the ratio of the CKM matrix elements $|V_{td}/V_{ts}|$
    - Current theoretical uncertainty dominated by the $B^0 \to \rho^0$ and $B^0 \to K^{*0}$ form factors uncertainties [JHEP 04 (2006) 046]

$B^0 \to \rho^0\gamma$ branching fraction

LHCb-PAPER-2025-017
In preparation

Preliminary

- Ratio of branching fraction

$$\frac{\mathcal{B}(B^0\to\rho^0\gamma)}{\mathcal{B}(B^0\to K^{*0}\gamma)} = \frac{N(B^0\to\rho^0(\pi^+\pi^-)\gamma)}{N(B^0\to K^{*0}(K^+\pi^-)\gamma)} \times \frac{\varepsilon(B^0\to K^{*0}(K^+\pi^-)\gamma)}{\varepsilon(B^0\to\rho^0(\pi^+\pi^-)\gamma)} \times \mathcal{R}_{\mathcal{B}},$$

Yields: simultaneous unbinned maximum-likelihood fit to B invariant mass

Efficiencies: simulation corrected for MC/data differences

$$\frac{\mathcal{B}(K^{*0}\to K^+\pi^-)}{\mathcal{B}(\rho^0\to\pi^+\pi^-)}$$

- Mass window selections
  - $m_{\pi\pi} \in [630{,}920]$ MeV/c², $m_{K\pi} \in [795.5{,}995.5]$ MeV/c² (related efficiencies are accounted for)
- Charm veto $m_{\pi\gamma\to\pi^0} > 2000$ MeV/c²
- Combinatorial background suppressed by a BDT which uses kinematic and isolation variables
- PID criteria (charged and neutral) optimized with respect to the specific backgrounds
- MC/data differences corrected thanks to kinematic weighting and PID calibration samples

	$B^0 \to \rho^0\gamma(\%)$
$B^0 \to K^*\gamma$	11
$B^0 \to \rho^0(\pi^+\pi^-)\pi^0$	12
$B^0_s \to \phi(\pi^+\pi^-\pi^0)\gamma$	13
$B^0 \to K^+\pi^-\pi^0$	0.4
$B^0 \to \rho^0\eta$	0.9

	$B^0 \to K^{*0}\gamma(\%)$
$B^0 \to K^+\pi^-\pi^0$	1.6
$B^0 \to K^*\eta$	1.6
$\bar{B}^0_s \to K^{*0}\gamma$	0.8
$\Lambda^0_b \to pK^-\gamma$	0.5
$B^0_s \to \phi\gamma$	0.4

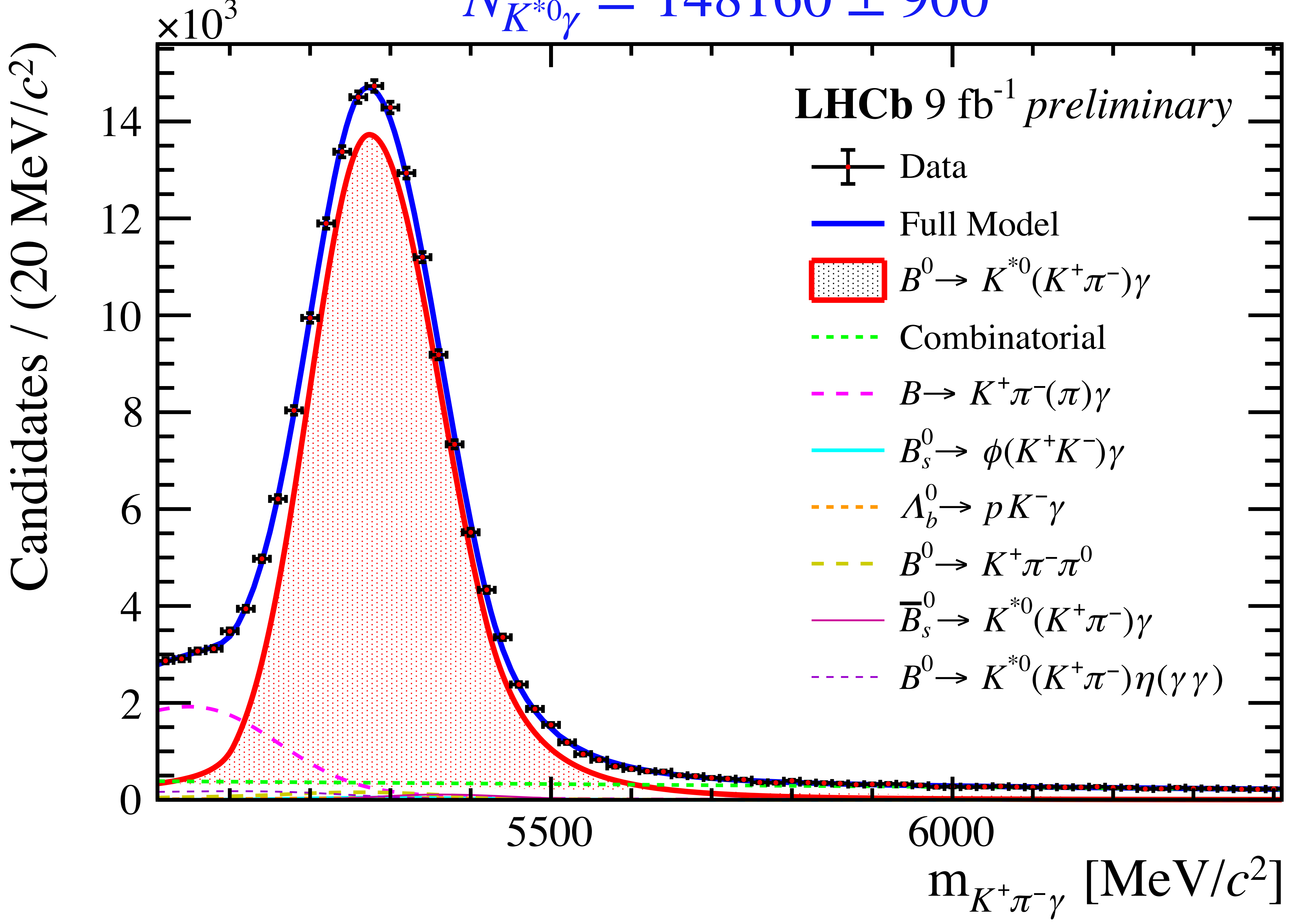
$B^0 \to \rho^0\gamma$ branching fraction

LHCb-PAPER-2025-017
In preparation

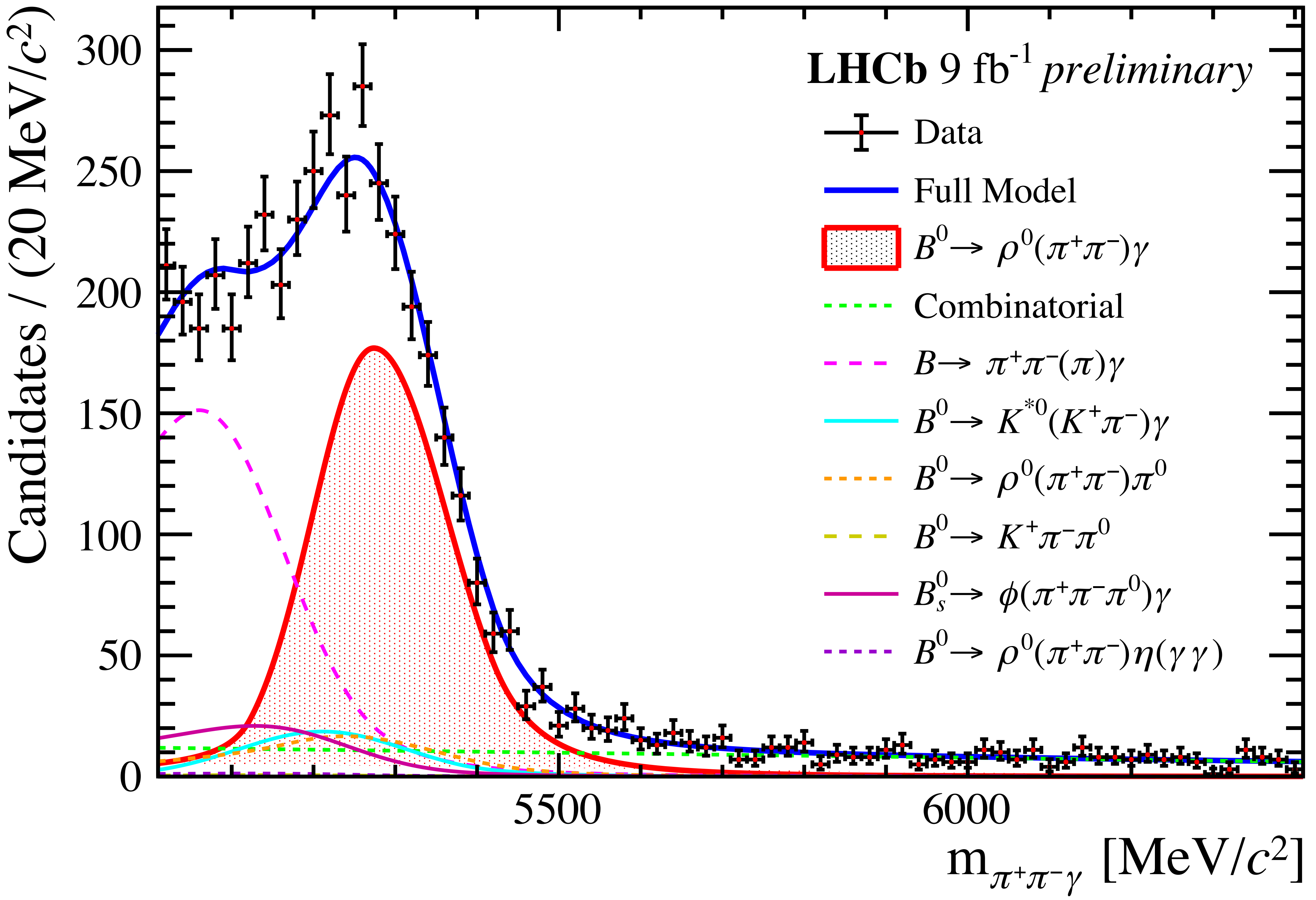
Preliminary

- Normalization and signal modes shared most of the signal shape parameters
- Misidentified background contributions to the $B^0 \to K^{*0}\gamma$ and $B^0 \to \rho^0\gamma$ samples are fixed as fractions of the fitted $B^0 \to K^{*0}\gamma$ yield
  - Shapes of those specific backgrounds are obtained from simulation

$N_{K^{*0}\gamma} = 148160 \pm 900$



$N_{\rho^0\gamma} = 1917 \pm 71$



$B^0 \to \rho^0\gamma$ branching fraction

LHCb-PAPER-2025-017
In preparation

Preliminary

- The ratio of branching fraction is measured as

$$\frac{\mathcal{B}(B^0 \to \rho^0\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} = 0.0189 \pm 0.0007 \pm 0.0005,$$

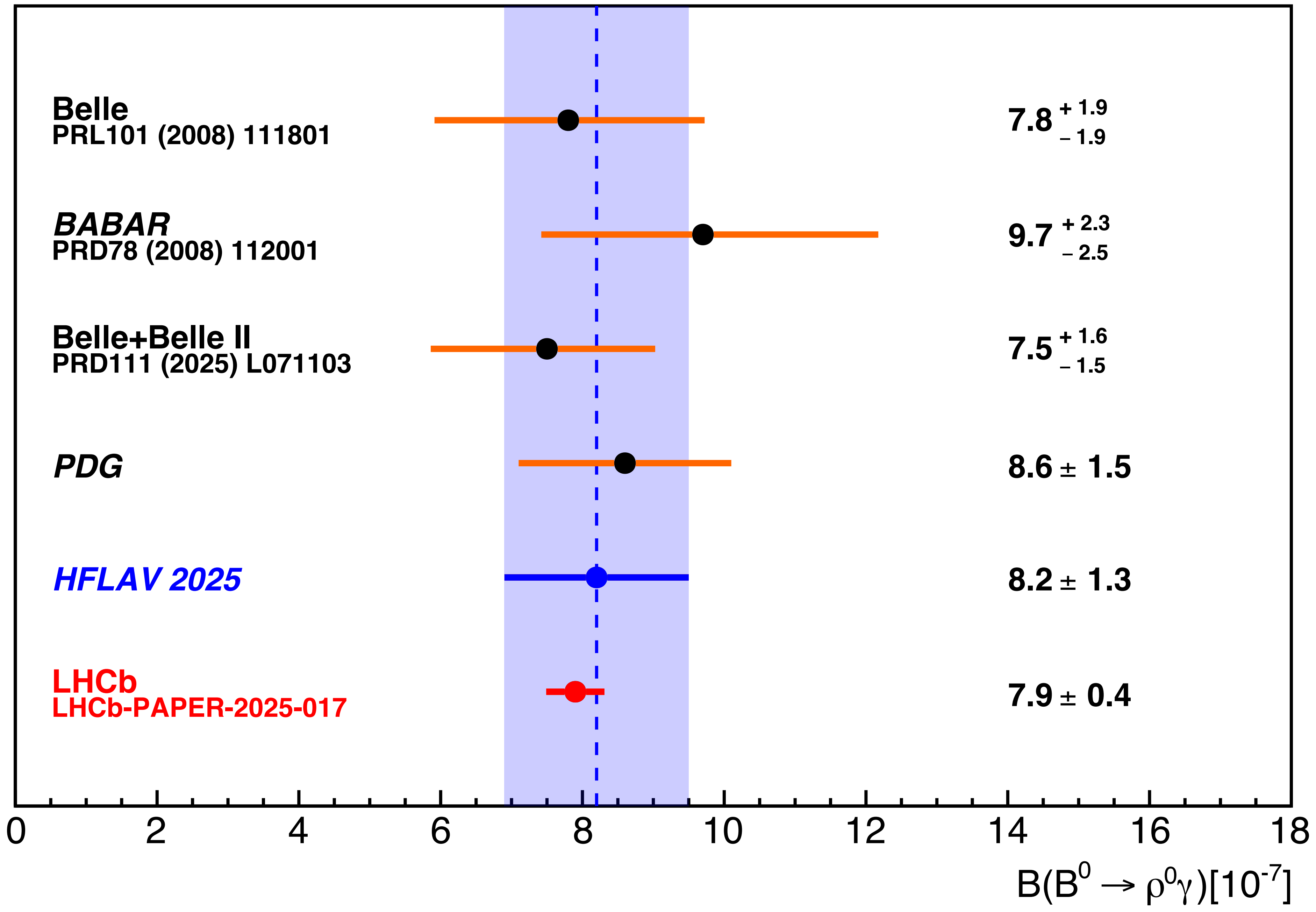
- Combining with the known $B^0 \to K^{*0}\gamma$ branching fraction from HFLAV, this gives

$$\mathcal{B}(B^0 \to \rho^0\gamma) = (7.9 \pm 0.3 \pm 0.2 \pm 0.2) \times 10^{-7},$$

The first uncertainty is statistical, the second systematic and the last one is due to the uncertainty $B^0 \to K^{*0}\gamma$ branching fraction

- Assuming $\rho^0 \to \pi^+\pi^-$ decay saturates the dipion spectrum in the $m_{\pi\pi}$ range used ($m_{\pi\pi} \in [630,920]$MeV/c²)

- **Most precise** measurement to date



Dominated by the 25% relative uncertainty on the $B^0 \to \rho^0(\pi^+\pi^-)\pi^0$ branching fraction

Systematics: Yield ratio

Source	Uncertainty [%]
Signal mass model	(+0.5, −0.6)
Background contributions	(+2.0, −2.2)
Background mass models	(+1.1, −0.8)
Total systematic uncertainty	(+2.3, −2.4)

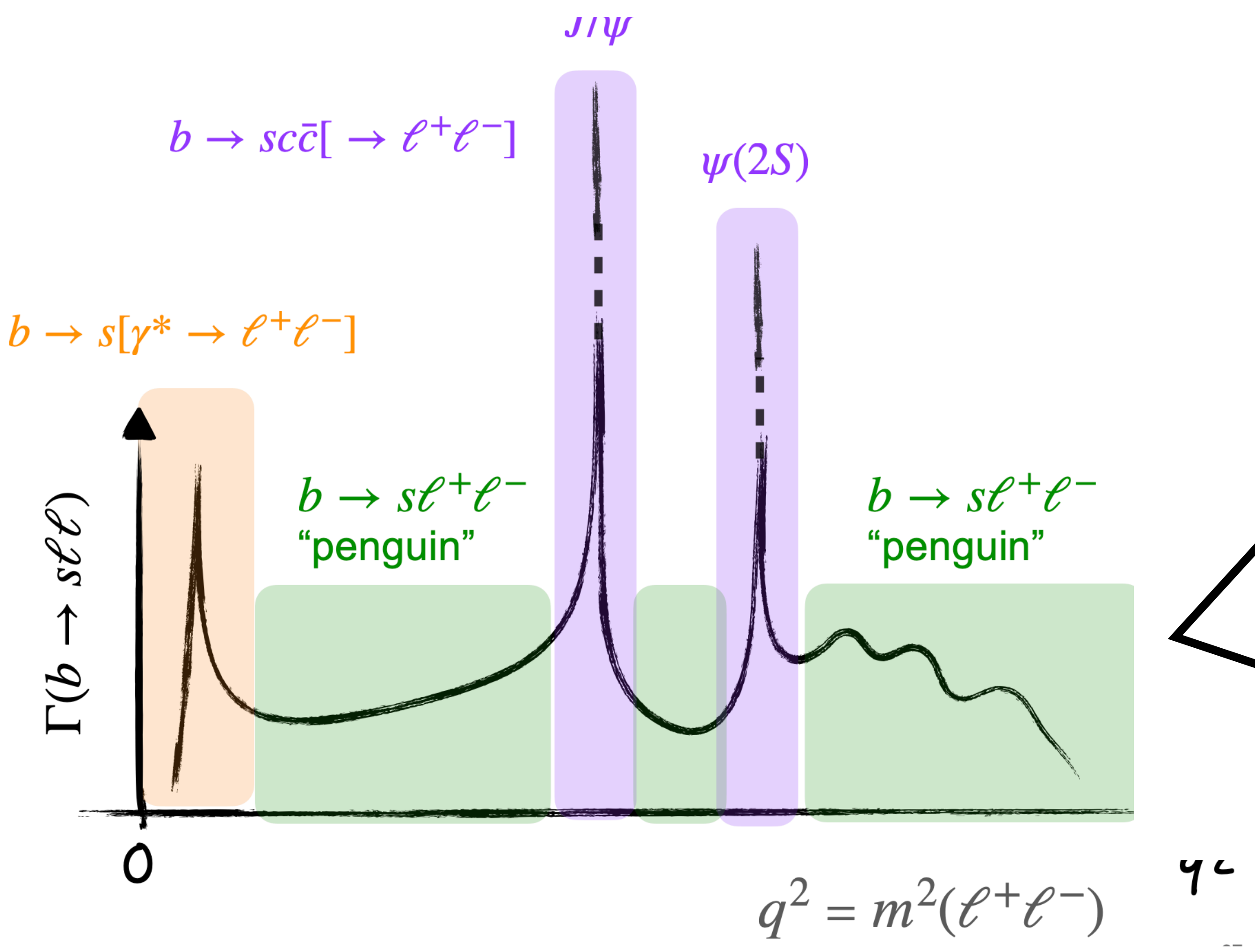
Efficiency ratio:

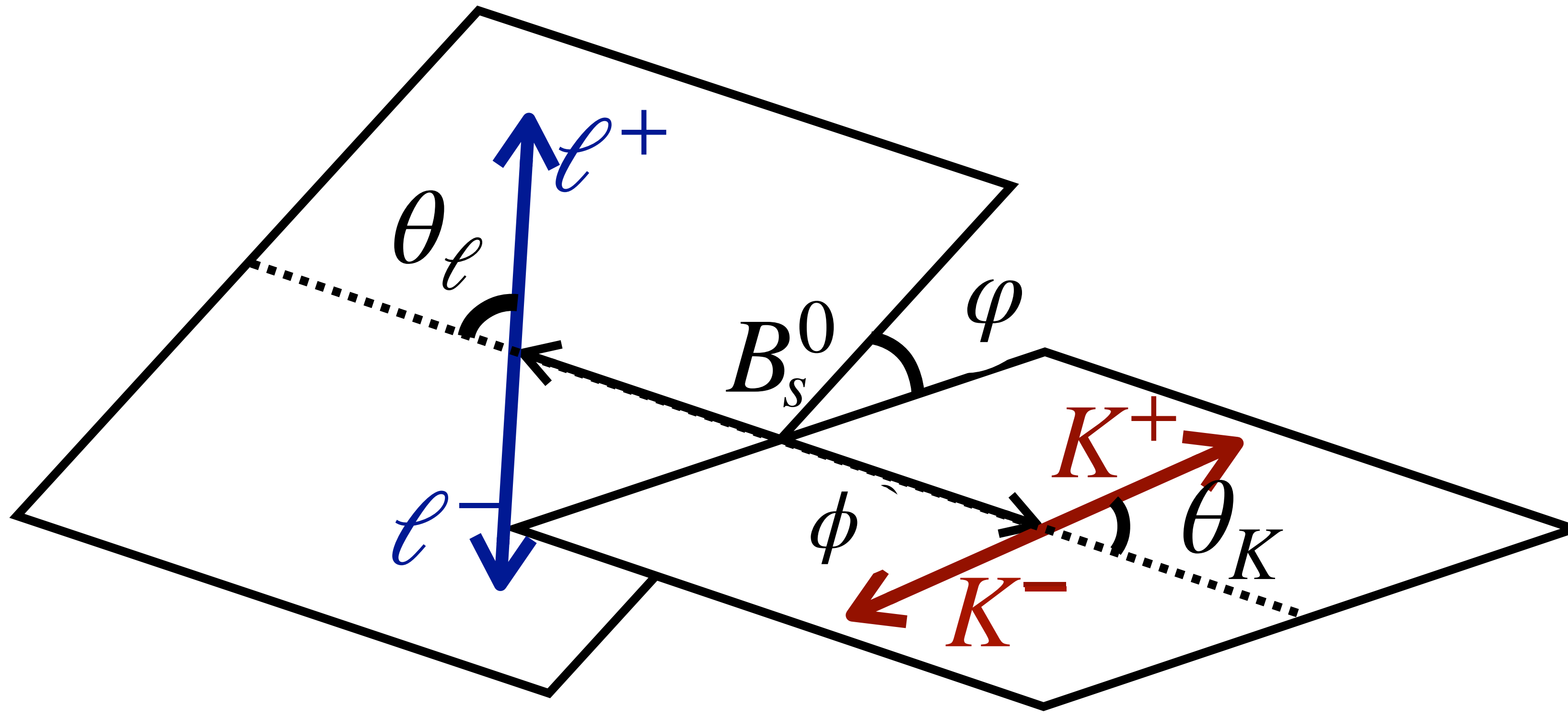
Source	Uncertainty [%]
Simulated samples size	(+0.8, −0.8)
Kinematics corrections	(+1.1, −0.2)
Kaon/pion reconstruction	(+0.3, −0.3)
Charged PID	(+0.7, −1.3)
Neutral PID	(+0.1, −0.1)
Total systematic uncertainty	(+1.6, −1.6)

Angular analysis of $B_s^0 \to \phi e^+ e^-$ decays

JHEP 03 (2025) 047

- Full Run 1+ 2 LHCb statistics (9 fb^{-1})
- First angular analysis of this decay mode at LHCb
- Cover a very low q^2 range [0.0009, 0.2615] GeV$^2/c^4$





- Untagged, time-integrated, CP-averaged angular differential rate

$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_L\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\varphi}} = \frac{9}{32\pi}\Bigg\{ & \frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \\
& + \left[\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K\right]\cos 2\theta_L \\
& + \frac{1}{2}(1-F_L)\,A_T^{(2)}\sin^2\theta_K\sin^2\theta_L\cos 2\tilde{\varphi} \\
& + (1-F_L)\,A_T^{\mathcal{R}eCP}\sin^2\theta_K\cos\theta_L \\
& + \frac{1}{2}(1-F_L)\,A_T^{\mathcal{I}mCP}\sin^2\theta_K\sin^2\theta_L\sin 2\tilde{\varphi}\Bigg\}.
\end{aligned}
$$

F_L : Longitudinal polarisation of ϕ meson

A_T^{ReCP}: related to the forward-backward asymmetry

$A_T^{(2)}$ and A_T^{ImCP} are sensitive to photon polarisation

$$A_T^{(2)}(q^2 \to 0) = \frac{2Re(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2} + \Delta_1^2,$$

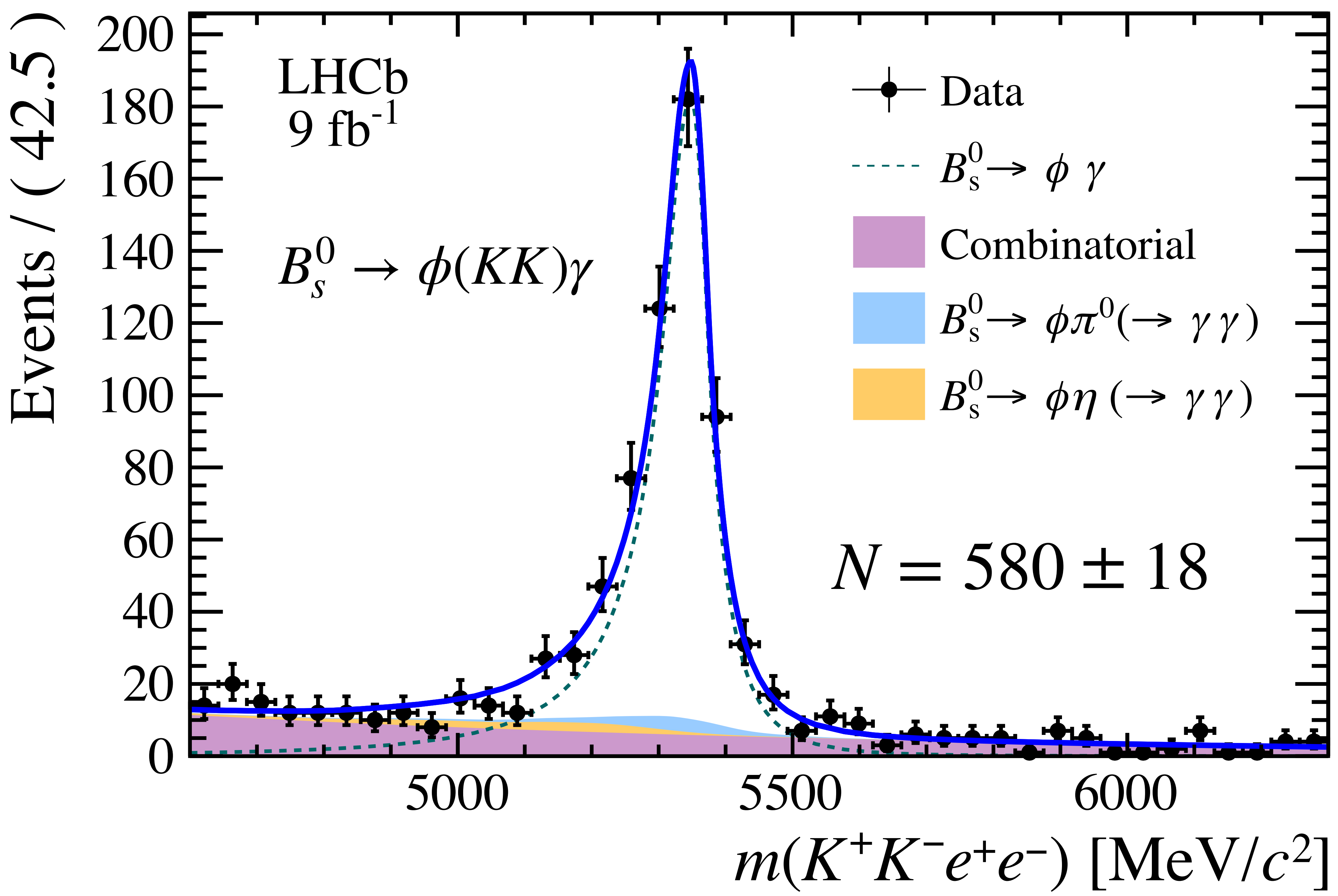
$$A_T^{ImCP}(q^2 \to 0) = \frac{2Im(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2} + \Delta_2^2,$$

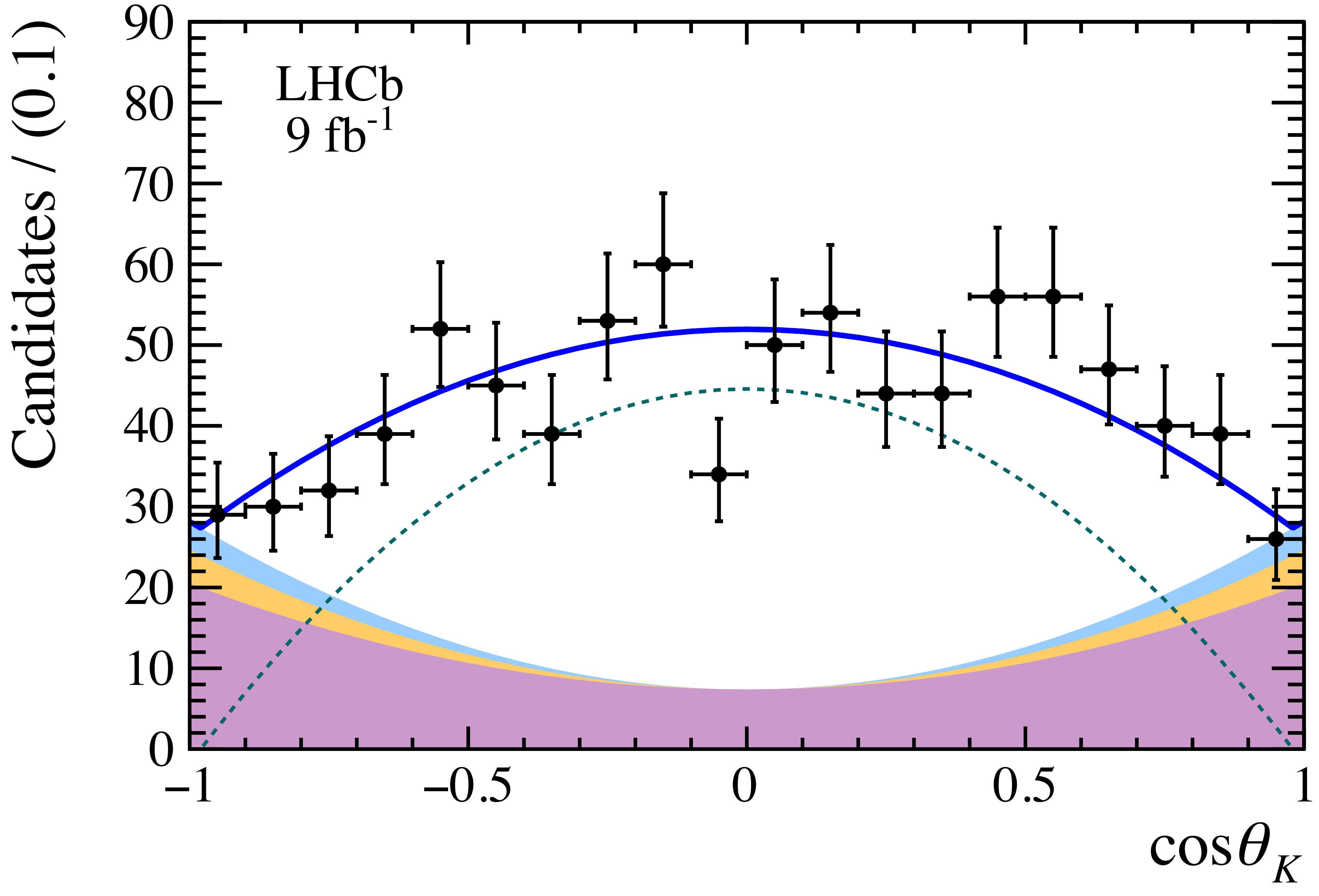
Δ_i due to Δm_s and $\Delta\Gamma_s$

Angular analysis of $B_s^0 \to \phi e^+ e^-$ decays

JHEP 03 (2025) 047

- Backgrounds are dominated by the combinatorial background, suppressed by BDT
- The radiative $B_s^0 \to \phi(KK)\gamma$ decay with converted photon (m_{ee}< 10 MeV/c^2) is used as control channel:



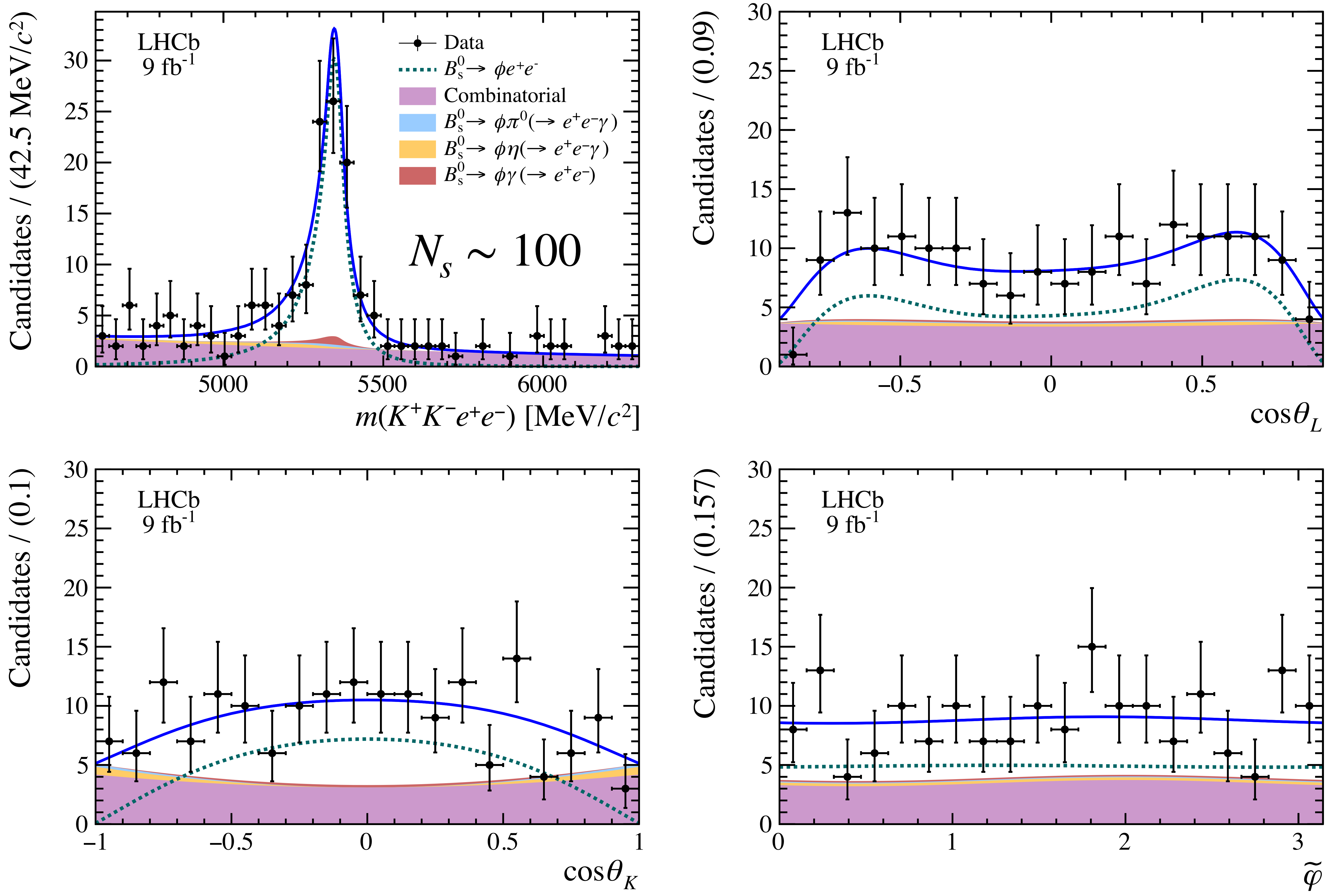


- $F_L[\phi\gamma_{\to e^+e^-}] = -0.01 \pm 0.02$ (stat): agrees well with a purely transverse polarisation of the ϕ meson, indicative of a real photon interaction

Angular analysis of $B_s^0 \to \phi e^+ e^-$ decays

JHEP 03 (2025) 047

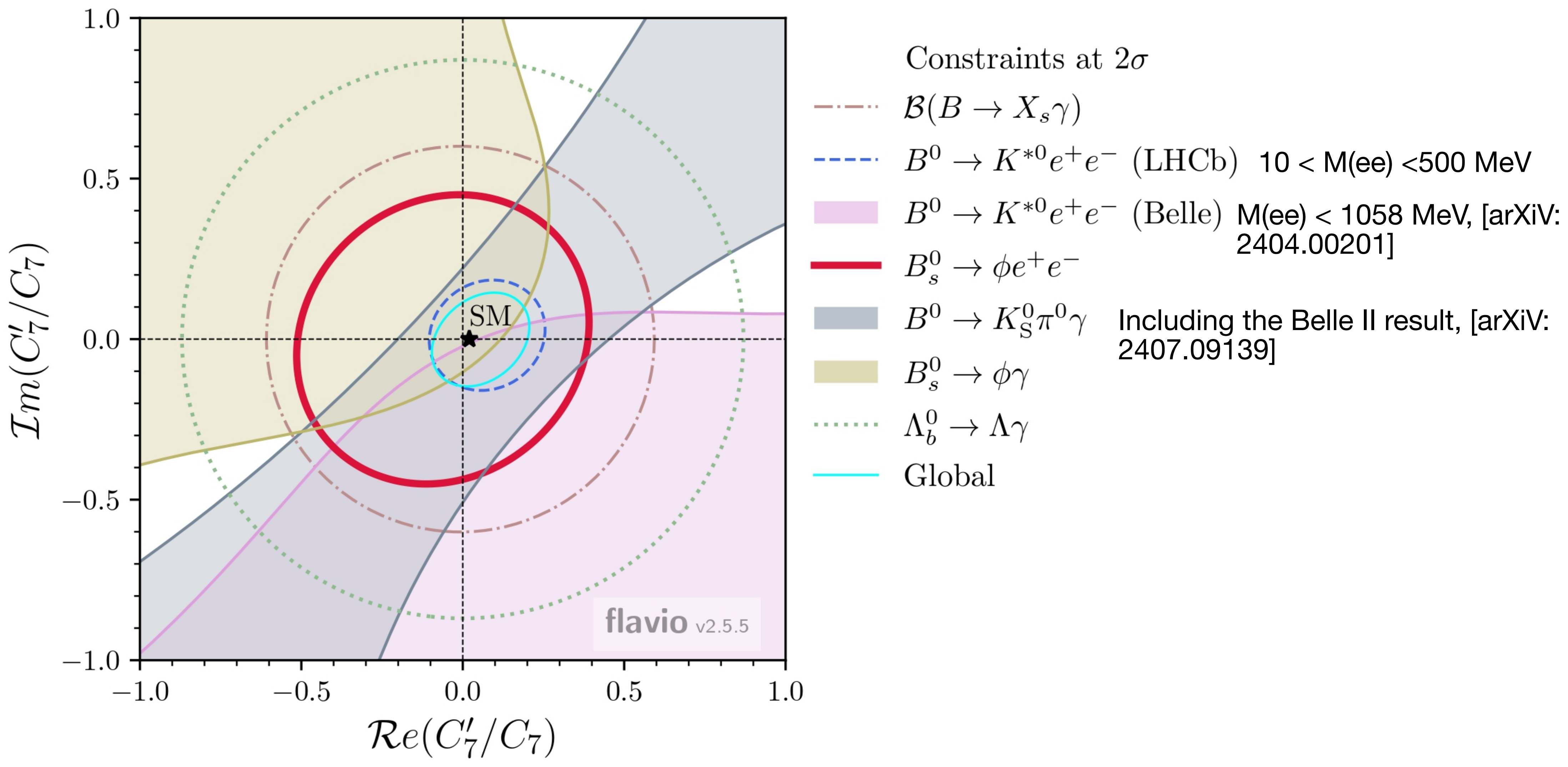
- 4D unbinned maximum likelihood fit to mass and angular variables



$$
\begin{aligned}
A_{\mathrm{T}}^{(2)} &= -0.045 \pm 0.235 \pm 0.014\,, \\
A_{\mathrm{T}}^{\mathcal{I}mCP} &= 0.002 \pm 0.247 \pm 0.016\,, \\
A_{\mathrm{T}}^{\mathcal{R}eCP} &= 0.116 \pm 0.155 \pm 0.006\,, \\
F_{\mathrm{L}} &< 11.5\% \text{ at } 90\% \text{ CL}\,.
\end{aligned}
$$

Dominant statistical uncertainties

SM predictions	
F_L	0.068
$A_T^{(2)}$	0.094
A_T^{ImCP}	0.000
A_T^{ReCP}	0.000

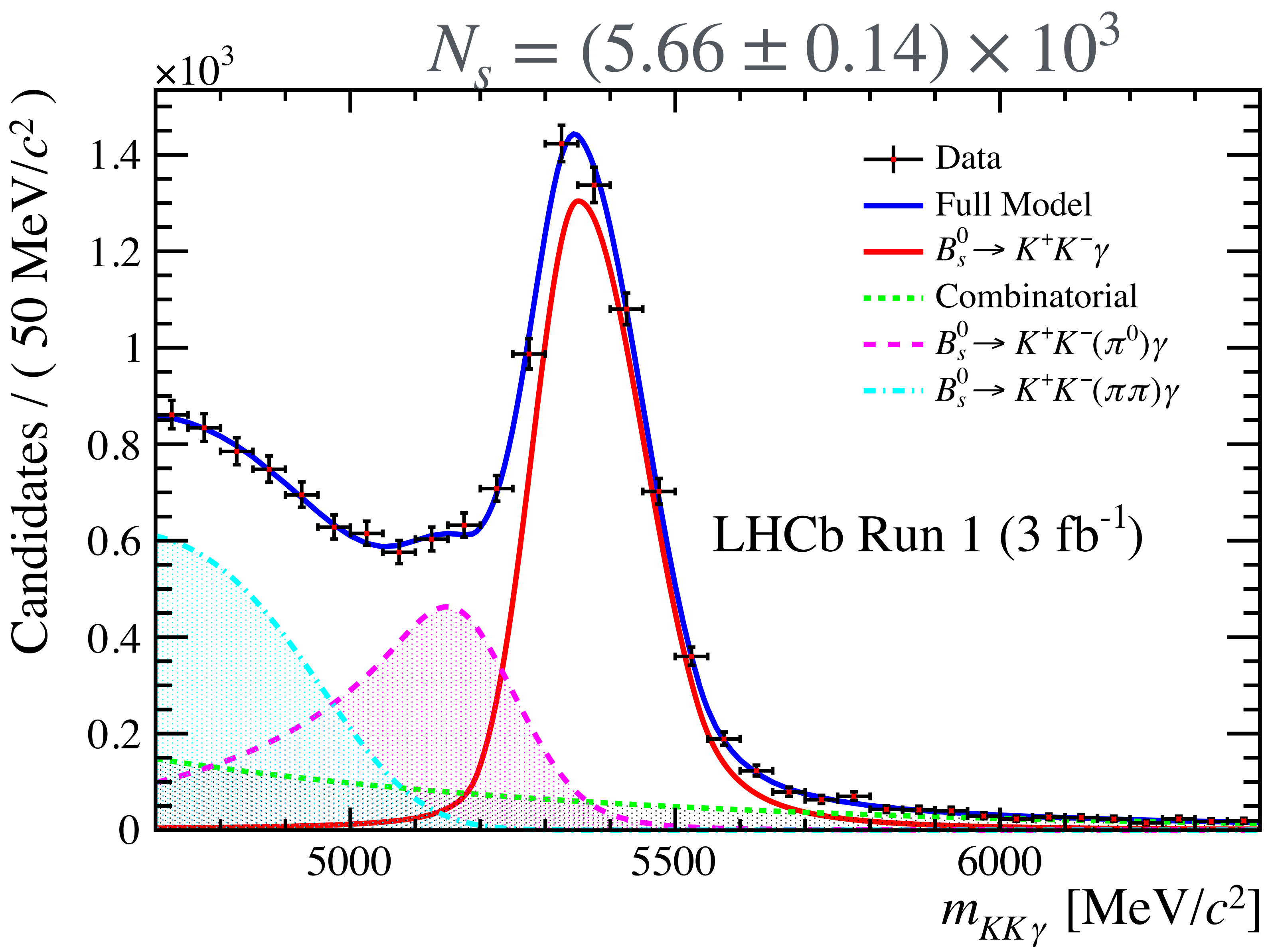


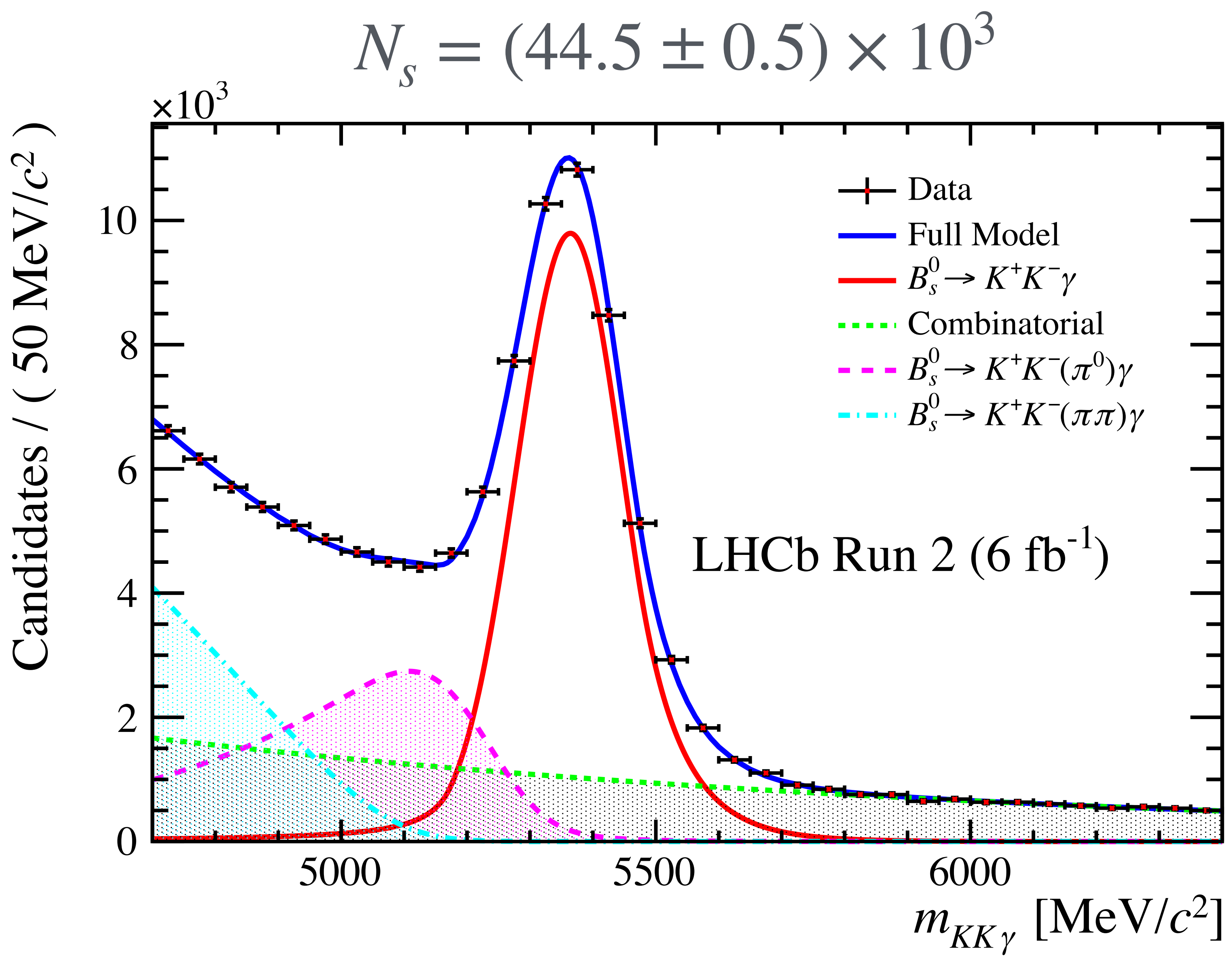
- **The results are compatible with the SM predictions.**

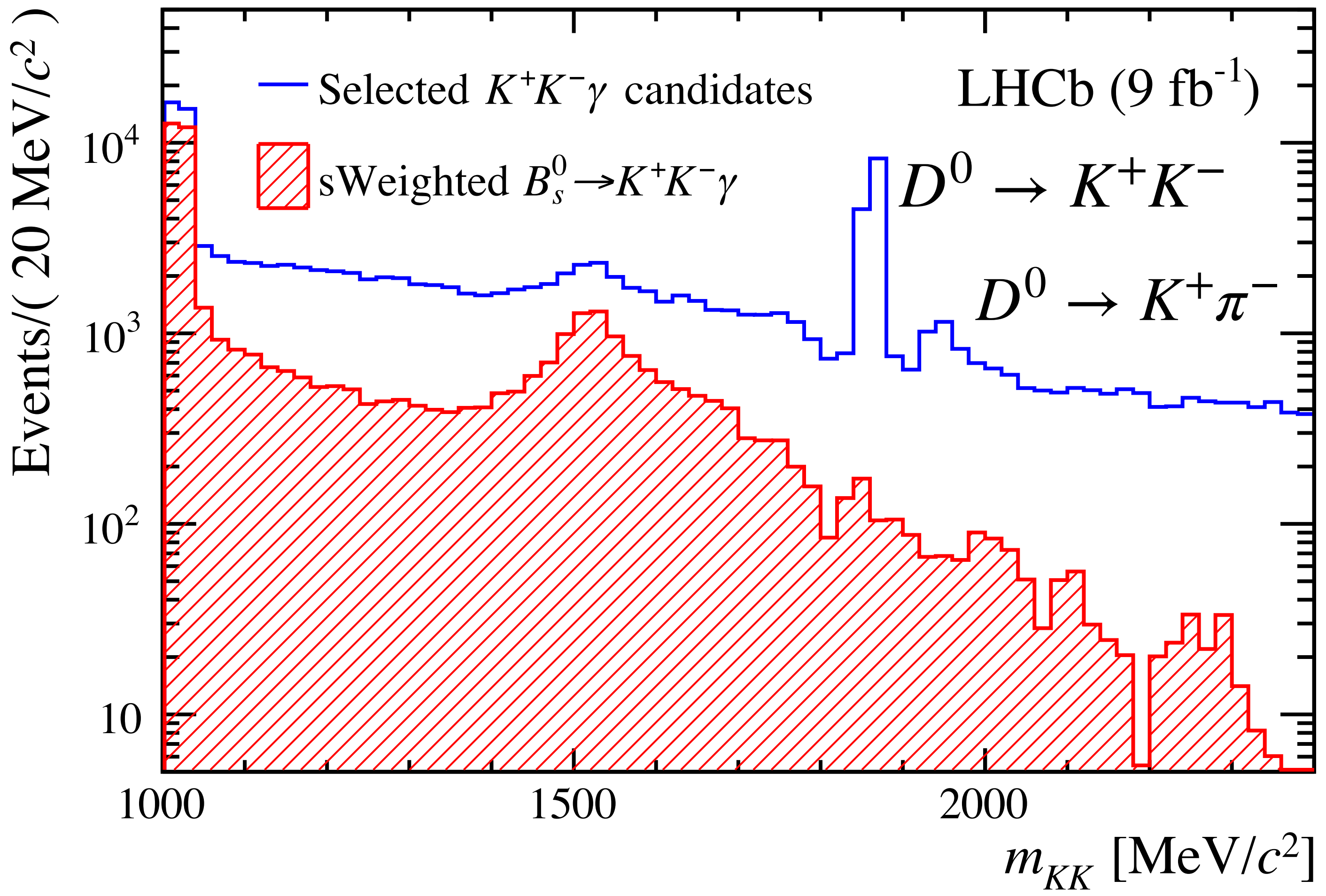
Amplitude analysis of $B_s^0 \to K^+K^-\gamma$ decays

JHEP 08 (2024) 093

- First observation by Belle (PRD 91 011101)
- First precise measurement of BR by LHCb based on ~700 events in the ϕ region collected in 2011 @ 7 TeV [Nuc. Phy. Sec. B 867 (2013), pp. 1-18]
- First amplitude analysis of this decay performed in LHCb using the full Run 1+ 2 LHCb statistics (9 fb^{-1})
- Combinatorial and partial reco. background are subtracted using sPlot method ($m_{KK} < 2400$ MeV/c²)
  - Clear structure around 1500 MeV/c², aside from $\phi(1020)$







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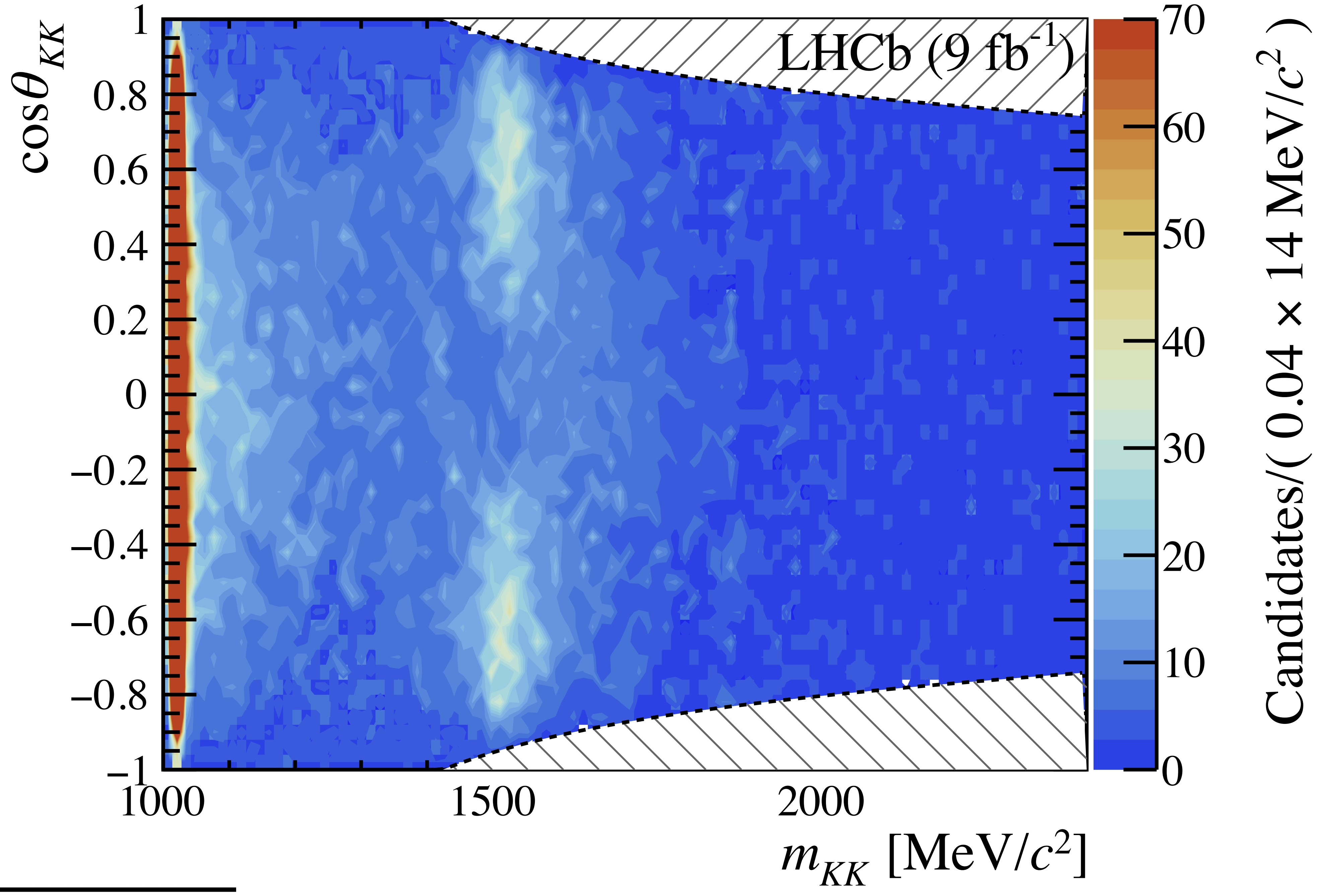
Amplitude analysis of $B_s^0 \to K^+K^-\gamma$ decays

- Phase space fully described by $(m_{KK}, |cos\theta_{KK}|)$:
  - Shaded region is the effect of charm veto ($m_{K\gamma\to\pi^0} > 2000$ MeV/c²)
  - Detector asymmetries cancelled out by folding over θ_{KK}
- Fit the amplitudes using isobar amplitude model approach

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

- Possible contributions from vector, tensor and higher spin states: 7 contributions included in the amplitude model
- MisID backgrounds are included in the fit

$$\mathcal{P}(m_{KK},\theta_{KK}) = \mathcal{N}_S\mathcal{P}_S + \sum_{BKG}\mathcal{N}_{BKG}\mathcal{P}_{BKG}$$



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^{++}
$(KK)_{NR}$	1^{--}

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

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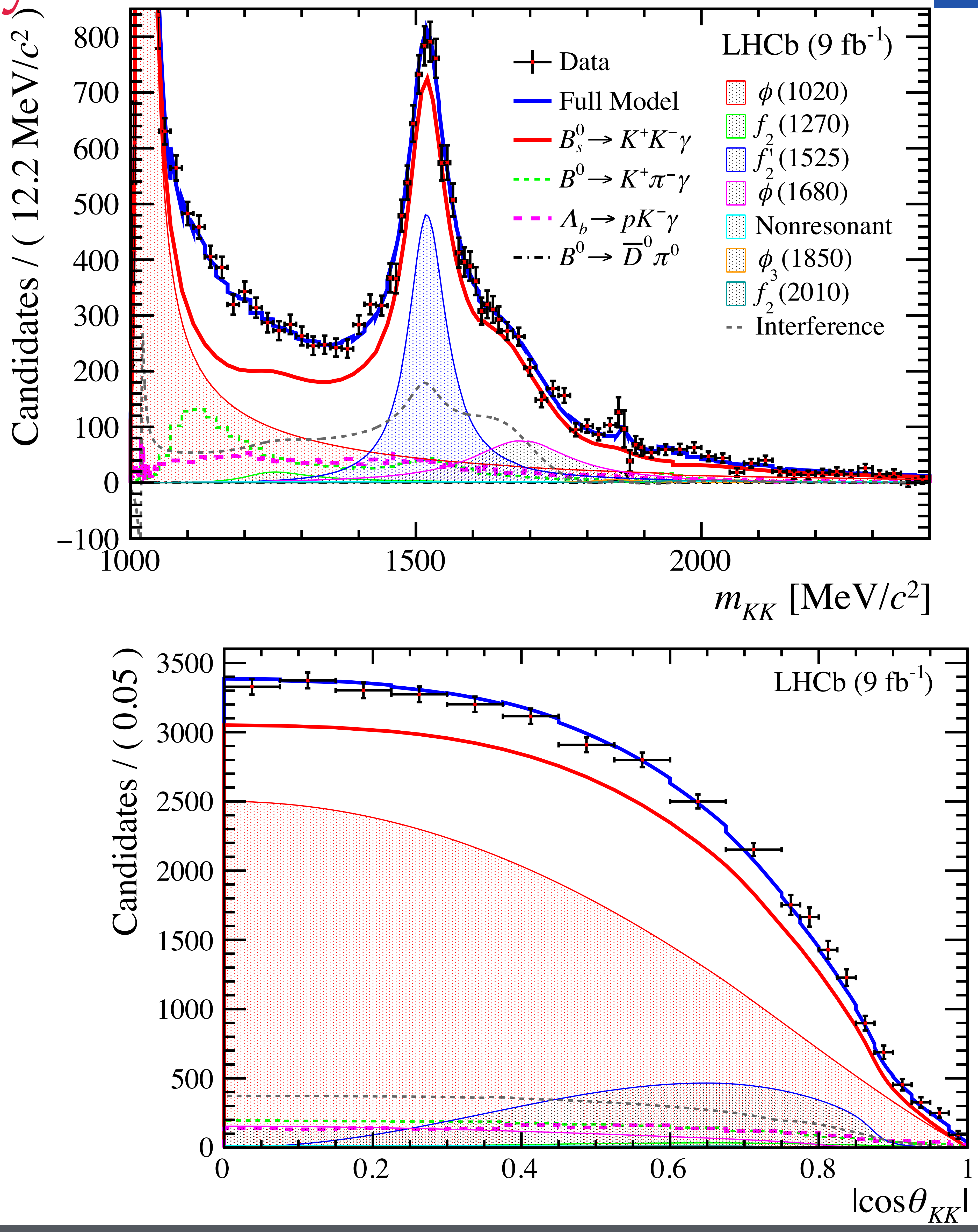
- Fit fractions and overall tensor contributions are extracted from the best fit
- Full results in backup, one has concerning tensors

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

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

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

- **First observation of the $B_s^0 \to f_2'(1525)\gamma$**
- **Mass and width of $\phi(1020)$ and $f_2'(1525)$ are in agreement with world averages**



Outlook and conclusions

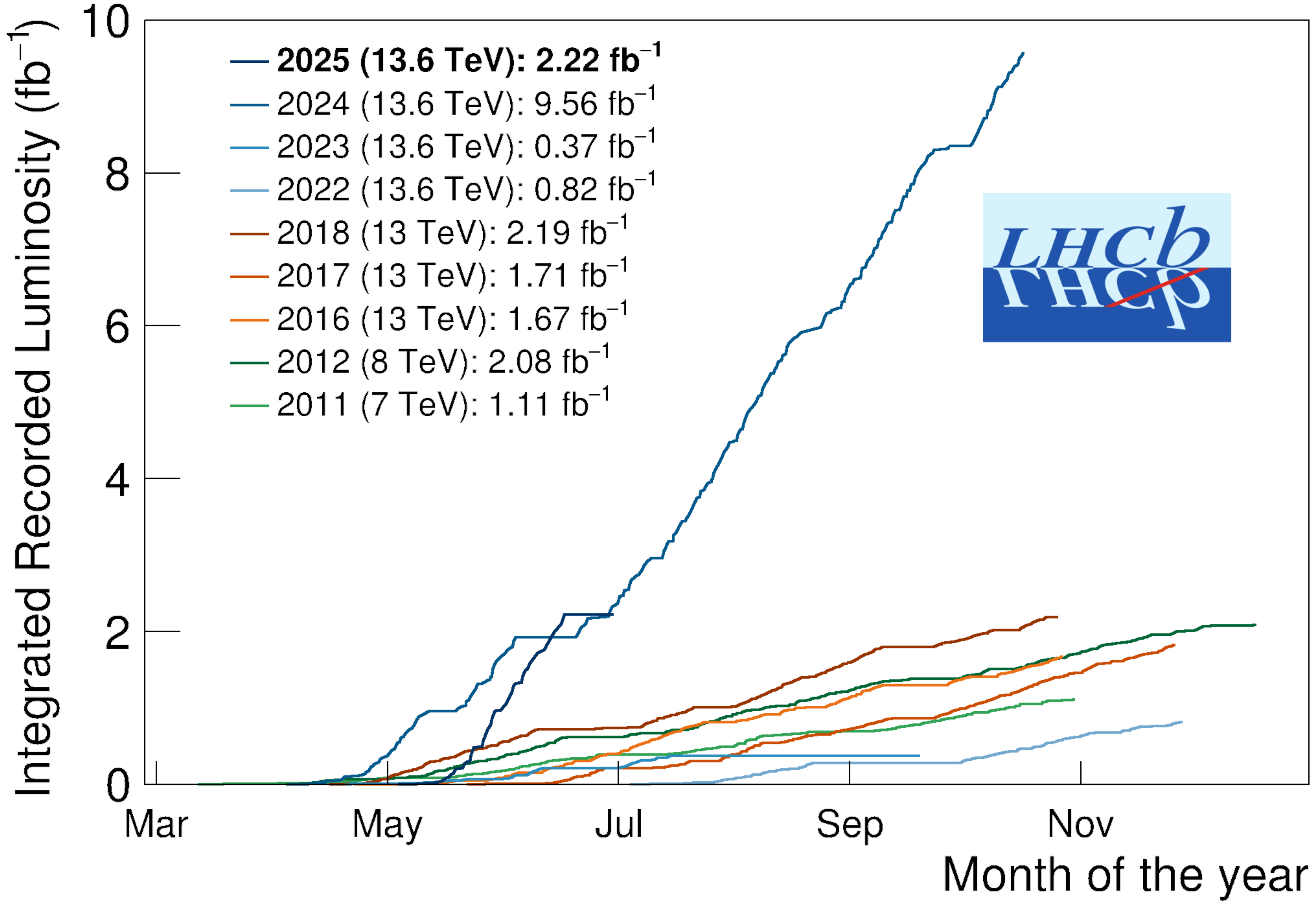
- Radiative decay offers a unique environment to look for BSM physics
- LHCb pushing limits towards unprecedented levels

- Today's presentation covers
  - Branching fraction measurement of $B^0 \to \rho^0\gamma$ (New) Preliminary
  - Constraint on photon polarisation in $b \to s\gamma$ using $B_s^0 \to \phi e^+e^-$
  - Amplitude analysis of $B_s^0 \to K^+K^-\gamma$

- More results from Run 1 and 2 data are expected soon

- Run 3 data taking is currently ongoing
  - **> 9** fb^{-1} data collected in 2024 and already **> 2.2** fb^{-1} in 2025
  - Upgraded detector and trigger system (fully software base) enhance signal efficiency
  - Open the door to new searches

    (rarer modes, use of converted photons, time dependent analyses)



Thank you for your attention

Backup

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

- Full result from amplitude analysis

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)
$\phi(1680)$	$3.8\ ^{+0.6}_{-0.5} \pm 0.7$	$5.4\ ^{+0.9}_{-0.6}\ ^{+1.0}_{-1.1}$	$137\ ^{+5}_{-6} \pm 8$
$\phi_3(1850)$	$0.3\ ^{+0.2}_{-0.1}\ ^{+0.2}_{-0.1}$	$0.4\ ^{+0.3}_{-0.2}\ ^{+0.3}_{-0.2}$	$-61\ ^{+16}_{-13}\ ^{+13}_{-12}$
$f_2(2010)$	$0.4 \pm 0.2\ ^{+0.2}_{-0.1}$	$0.6\ ^{+0.3}_{-0.2}\ ^{+0.3}_{-0.2}$	$43\ ^{+30}_{-24}\ ^{+52}_{-59}$
$(\mathrm{KK})_{\mathrm{NR}}$	$0.5\ ^{+0.4}_{-0.2}\ ^{+0.3}_{-0.2}$	$0.6\ ^{+0.5}_{-0.3}\ ^{+0.5}_{-0.3}$	$165\ ^{+6}_{-16} \pm 9$