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Radiative Decays at LHCb

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LHCb

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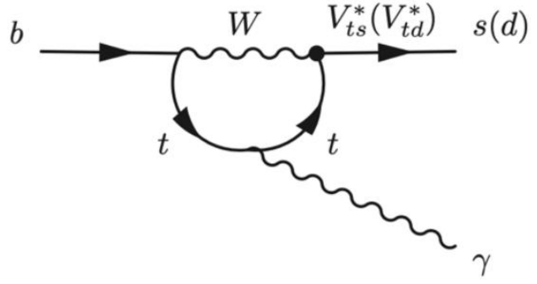
Radiative b-hadron decays

$\boldsymbol{b \to s(d)\gamma}$ transitions are **Flavour Changing Neutral Current (FCNC)**

- Highly suppressed in the SM (BR < 10^{-5})
- Sensitive to NP
- Access to test the couplings to 3rd generation quarks

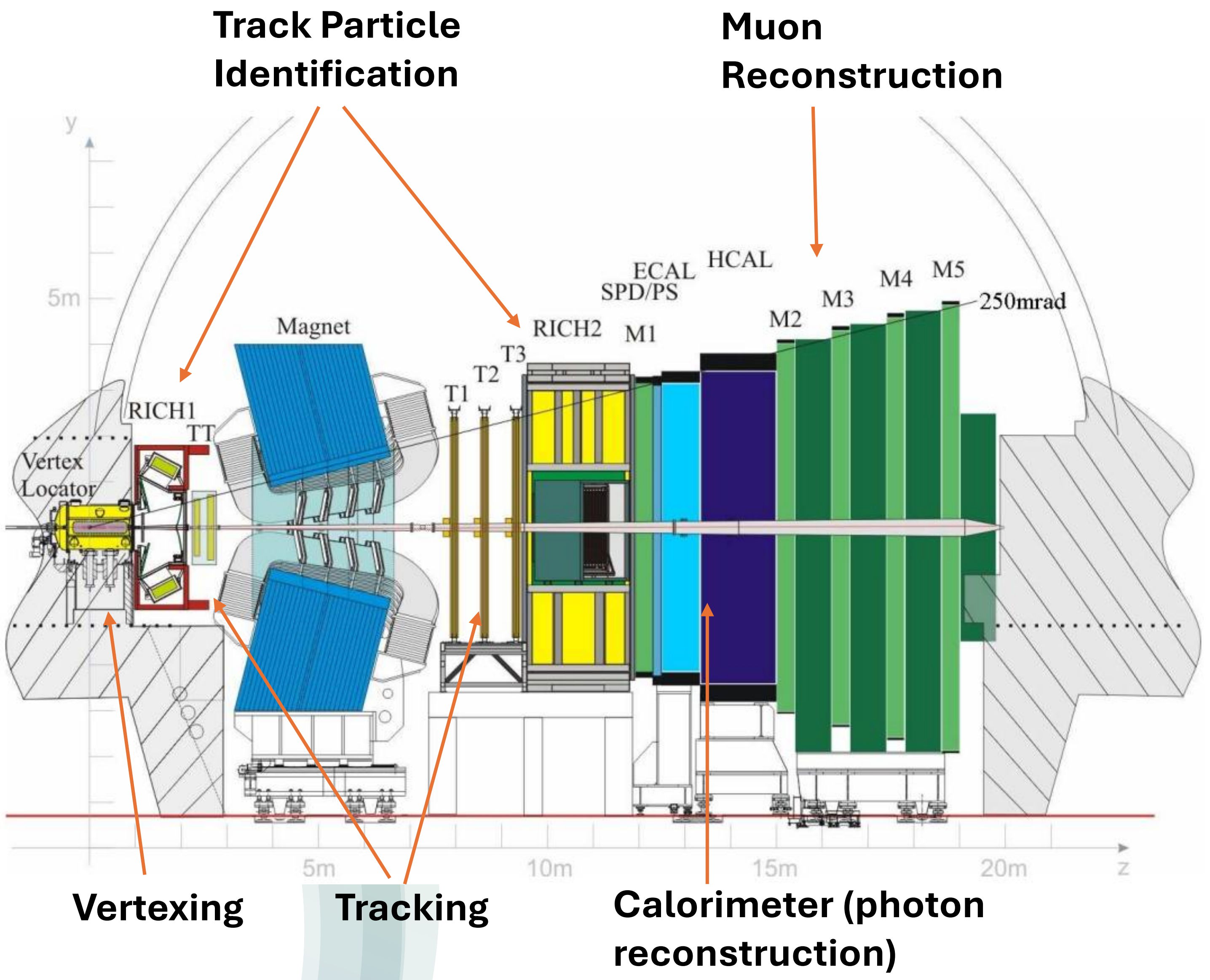


Observables:

Branching ratios	Photon Polarisation	CP asymmetries
$\propto (\lvert C_7\rvert^2 + \lvert C_7'\rvert^2)$	$\propto \frac{1 - \lvert C_7'\rvert^2/\lvert C_7\rvert^2}{1 + \lvert C_7'\rvert^2/\lvert C_7\rvert^2}$	$\propto Im\,\frac{C_7 C_7'}{\lvert C_7\rvert^2 + \lvert C_7'\rvert^2}$

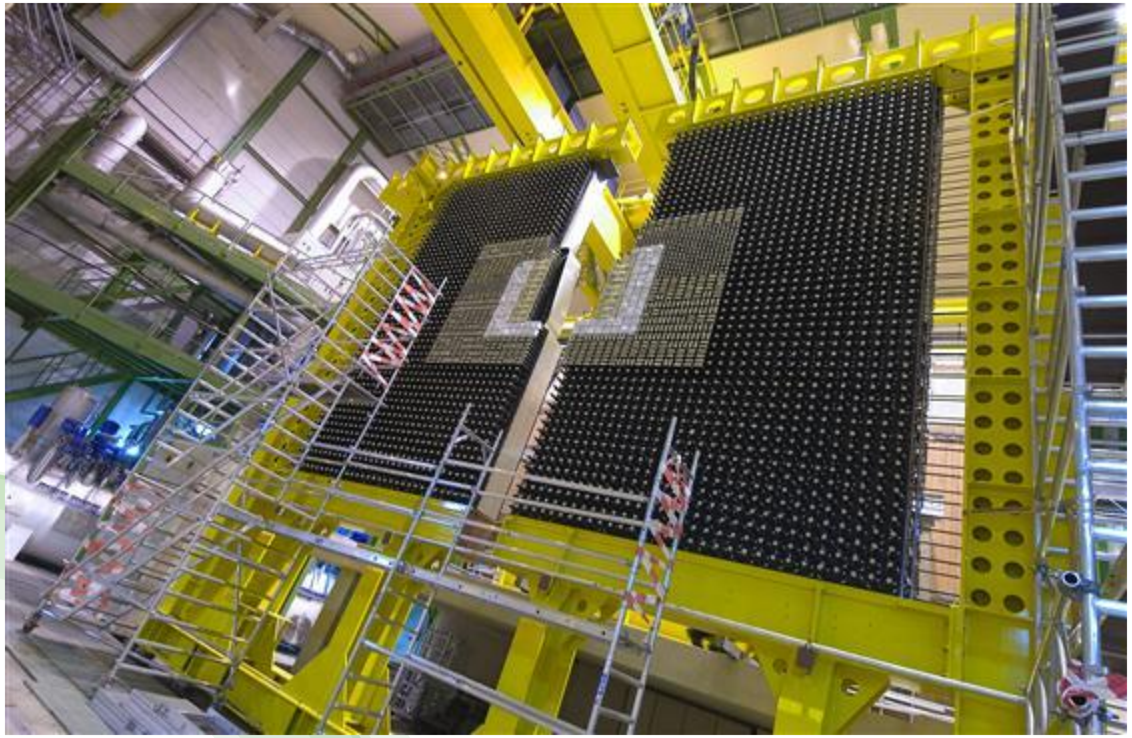
$$H_{eff} \propto V_{tb} V_{ts} \sum_i (C_i O_i + C_i' O_i')$$

Radiative b-hadron decays at LHCb



- Designed for study ***b*** and ***c*** hadrons
- Forward arm spectrometer pseudorapidity $2 < \eta < 5$
- Good vertex resolution $\sigma_{IP} = 20\ \mu m$
- Excellent momentum resolution $\frac{\Delta p}{p} = 0.5\% - 1\%\ (5 - 200 GeV/c)$
- Efficient particle identification
- $\epsilon_{tracking} \sim 96\%$

Electromagnetic Calorimeter at LHCb



- Shashlik technology with 4x4, 6x6 and 12x12 cm^2 cell size
- photon energy resolution $\frac{\sigma E}{E} = 1\% + 10\%/\sqrt{E}$
- Optimised for π^0 and γ identification in the few GeV to few 100 GeV
- Large array of ~ 50 m^2 with 3312 modules and 6016 channels

Upgrade II

- Timing capabilities with O(20) ps resolution
- Increased granularity in the central region with denser absorber (Upgrade Ib)

Radiative b-hadron decays

Recent Results

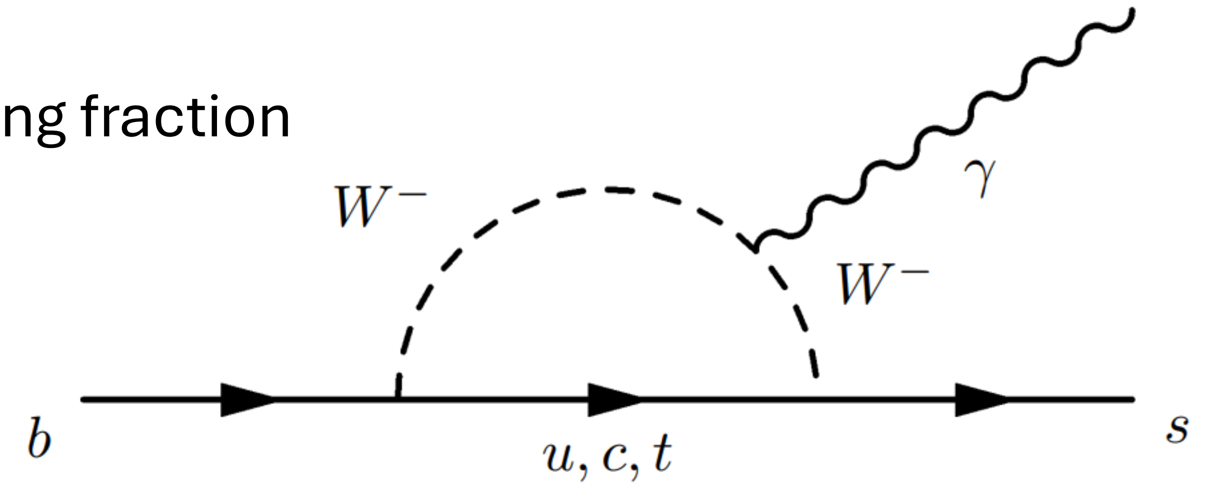
- Measurement of the $B^0 \to \rho(770)^0\gamma$ branching fraction [Submitted to JHEP] https://arxiv.org/abs/2507.14401
- Search for the $B_s^0 \to K^-\pi^+\gamma$ decay with converted photons [LHCb-PAPER-2025-056 in preparation]

To constraint $|V_{td}/V_{ts}|^2$

Currently Analysis:

Measurement of the $\boldsymbol{\Lambda_b^0} \to \boldsymbol{\Lambda^0\gamma}$ branching fraction

Many different theoretical predictions



Measurement of the $B^0 \to \rho(770)^0\gamma$ branching fraction [Submitted to JHEP] https://arxiv.org/abs/2507.14401

- First measurement associated to the transitions $b \to d\gamma$ in LHCb
- First observation by Belle and BaBar

A recent combination of the measurements using Belle II:
$\mathrm{B}(B^0 \to \rho^0\gamma) = (8.2 \pm 1.3) \times 10^{-7}$

- Using Run 1+ 2 LHCb data (9 fb^{-1})
- Extraction of the ratio of the branching fraction

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

Ratio of Signal Yields: From simultaneous mass fit to data

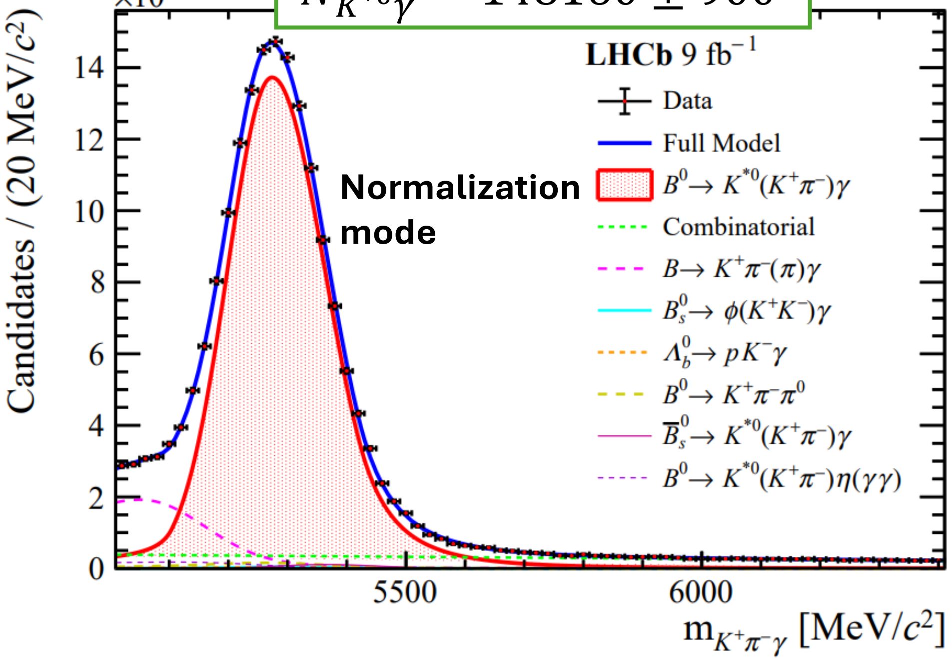
Efficiencies: from simulation and data

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

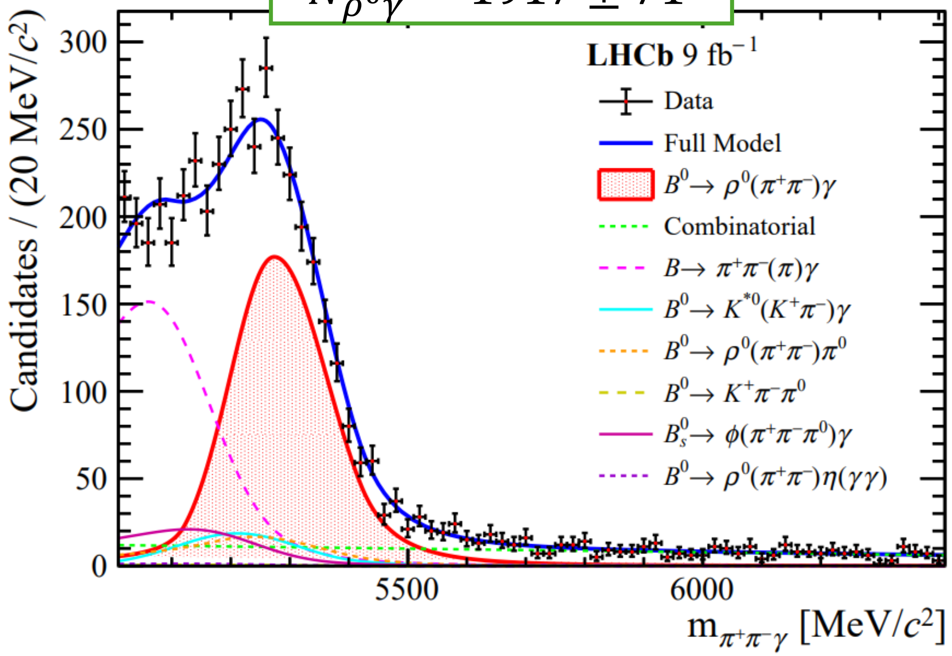
Measurement of the $B^0 \to \rho(770)^0\gamma$ branching fraction [Submitted to JHEP] https://arxiv.org/abs/2507.14401

- Normalization and signal modes shared most of the signal shape parameters
- Most individual background contributions fixed as fraction of the $B^0 \to K^{*0}(892)\gamma$ yields
  Shapes of specific backgrounds obtained from simulation

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



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



Statistical Systematic

$$\frac{N(B^0 \to \rho^0(\pi^+\pi^-)\gamma)}{N(B^0 \to K^{*0}(K^+\pi^-)\gamma)} = 0.0129 \pm 0.0005 \pm 0.0003$$

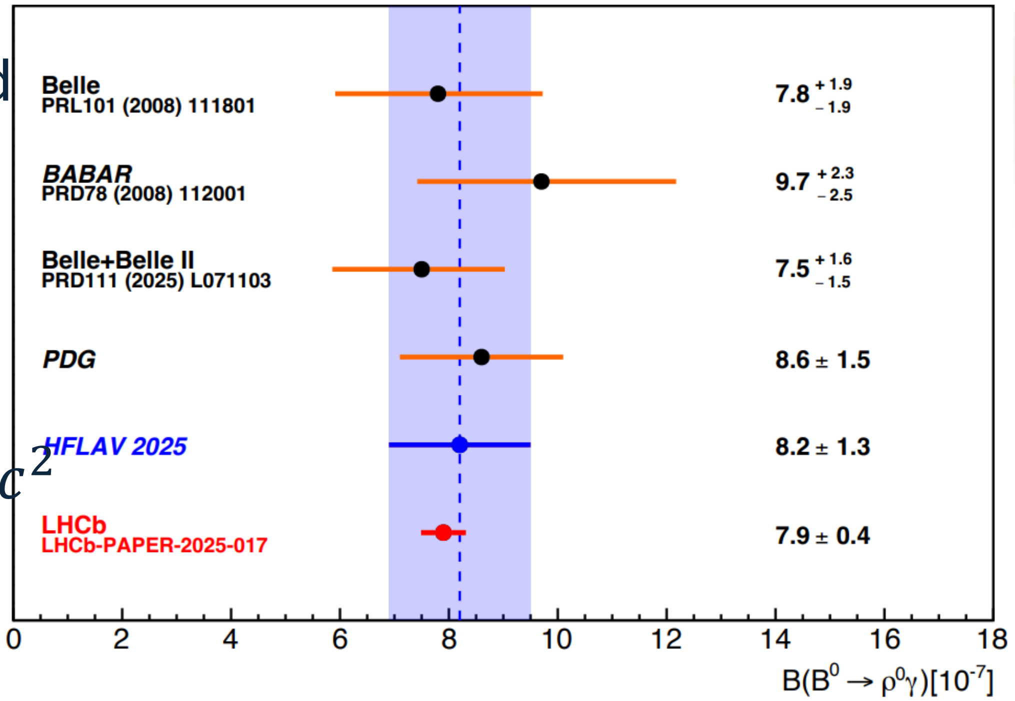
Measurement of the $B^0 \to \rho(770)^0\gamma$ branching fraction [Submitted to JHEP] https://arxiv.org/abs/2507.14401

- Combining the ratio of branching fraction measured with the known branching fraction for $B^0 \to K^{*0}\gamma$

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

Statistical   Systematic

- Assuming $\rho^0 \to \pi^+\pi^-$ decay saturates the dipion spectrum in the range used $m_{\pi\pi} \in [630,920]\ MeV/c^2$
- Most precise + good agreement with existing measurements
- Systematics uncertainties



Limited knowledge of the branching fraction of the $B^0 \to \rho^0(\pi^+\pi^-)\pi^0$ decay mode

Efficiency ratio

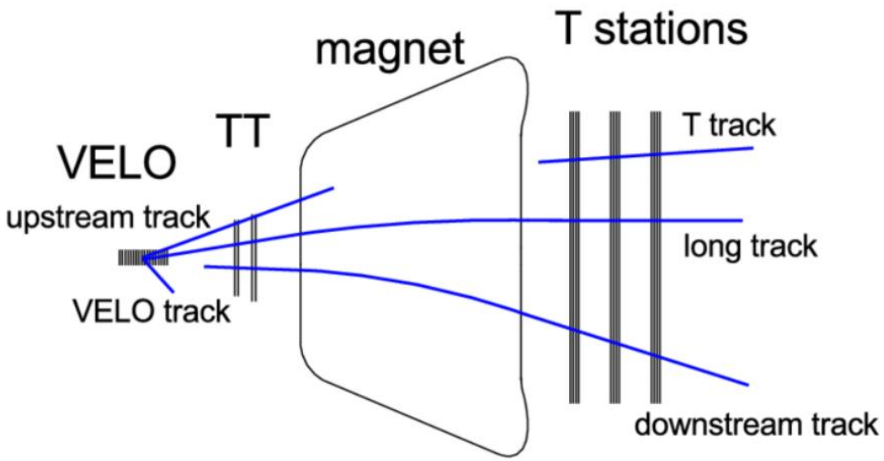
Source	Uncertainty [%]
Signal mass model	(+0.5, −0.6)
Background contributions	(+2.0, −2.2)
Background mass models	(+1.1, −0.8)
Total systematic uncertainty	(+2.3, −2.4)

Yield 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)

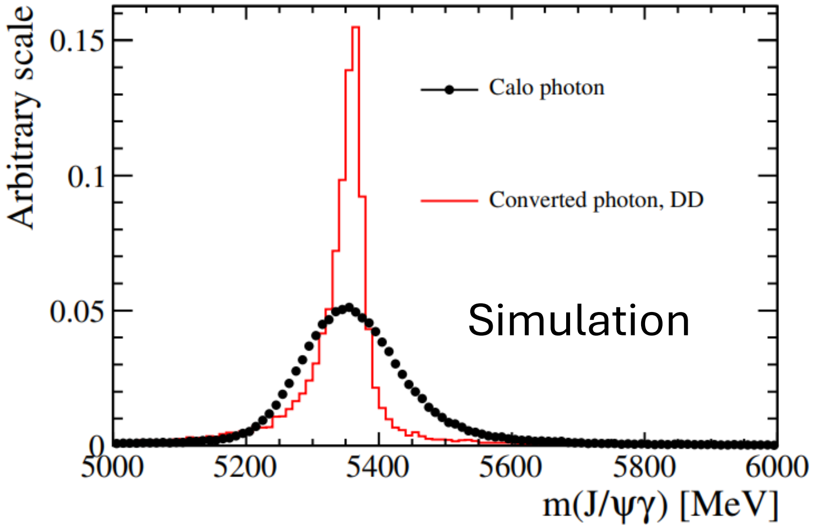
Search for the $B_s^0 \to K^-\pi^+\gamma$ decay with converted photons
[LHCb-PAPER-2025-056 in preparation]

- First evidence of the $B_s^0 \to K^-\pi^+\gamma$
- Using Run 1+ 2 LHCb data (9 fb^{-1})
- Use photons converting to e^+e^-
  - **Better resolution** (by a factor 3)
  - Reduced yields (by a factor of 10)



Improved resolution by rejecting electrons with bremsstrahlung

Downstream conversions emit less bremsstrahlung



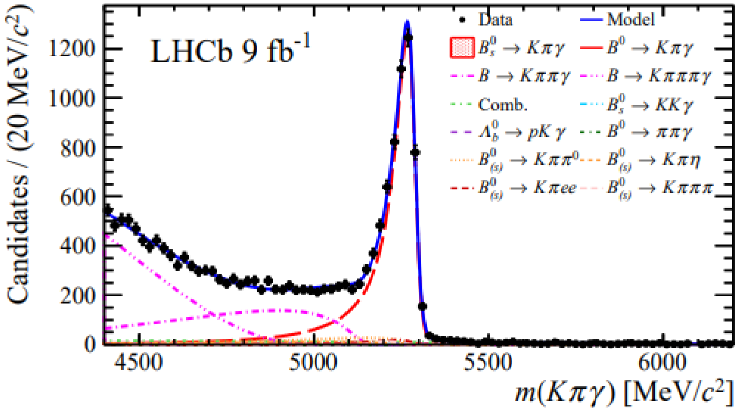
- Analyse separately *low* (796 < m($K\pi$) < 996 MeV) and *high* (996 < m($K\pi$) < 1800 MeV)

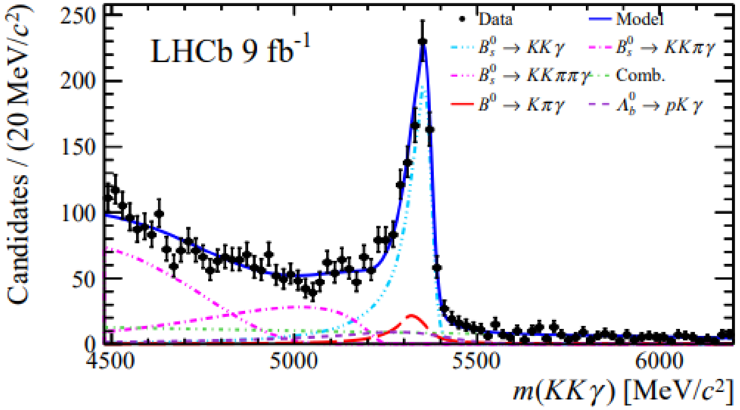
Search for the $B_s^0 \to K^- \pi^+ \gamma$ decay with converted photons
[LHCb-PAPER-2025-056 in preparation]

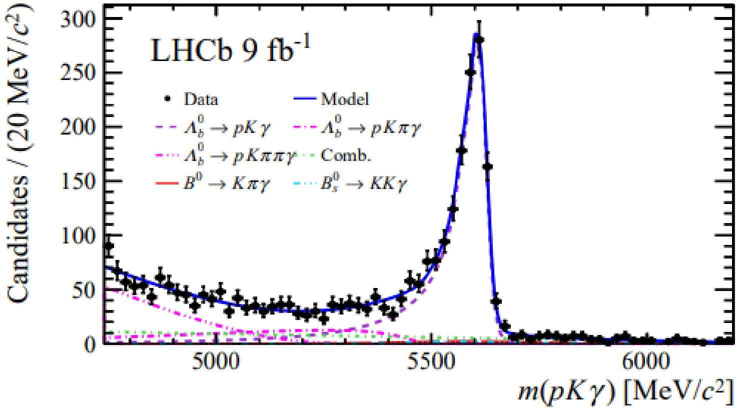
Background subtraction

- Misidentified $B_s^0 \to K^- K^+ \gamma$ and $\Lambda_b^0 \to p K^- \gamma$ decays reduced using information from RICH

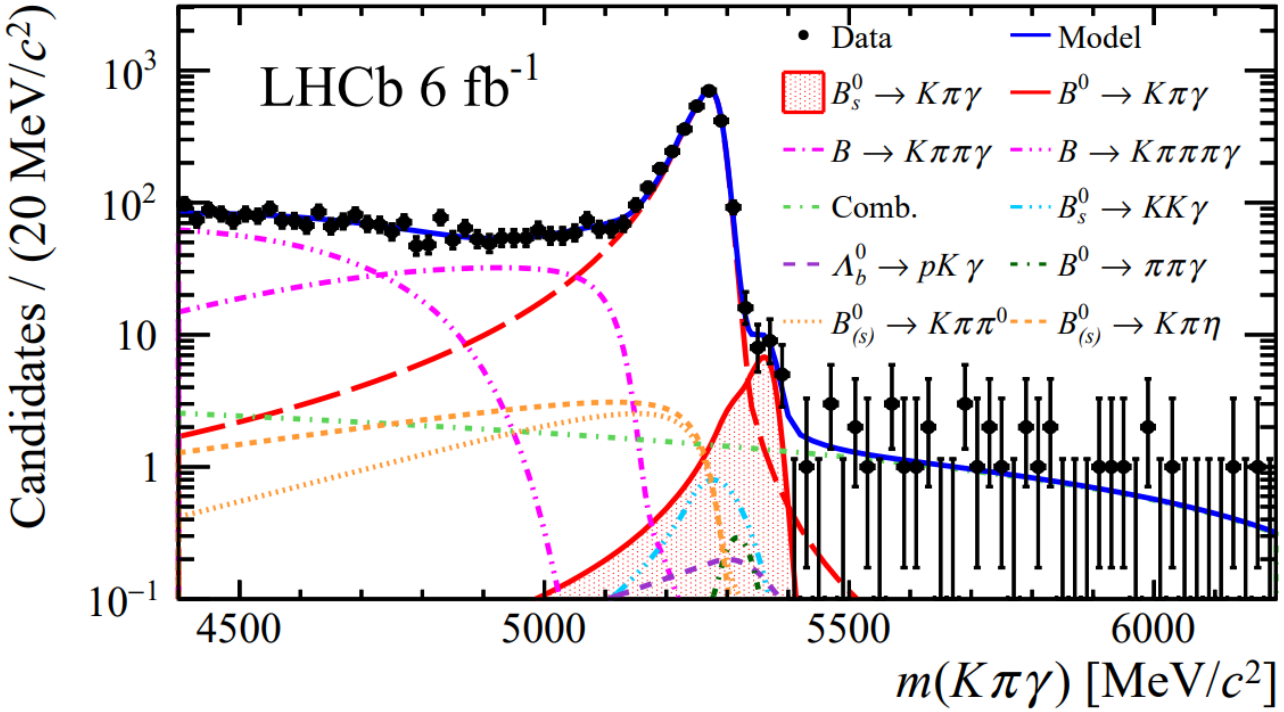
- Combinatorial background: reduced by > 95% with boosted decision tree (BDT) classifier trained on kinematic and topological properties of decay







Search for the $B_s^0 \to K^-\pi^+\gamma$ decay with converted photons
[LHCb-PAPER-2025-056 in preparation]



- 38 ± 18 signal decays
  (32 ± 11 Run 2 downstream low-m($K^-\pi^+$))
- In agreement with SM predictions
- 3.5 standard deviations significance

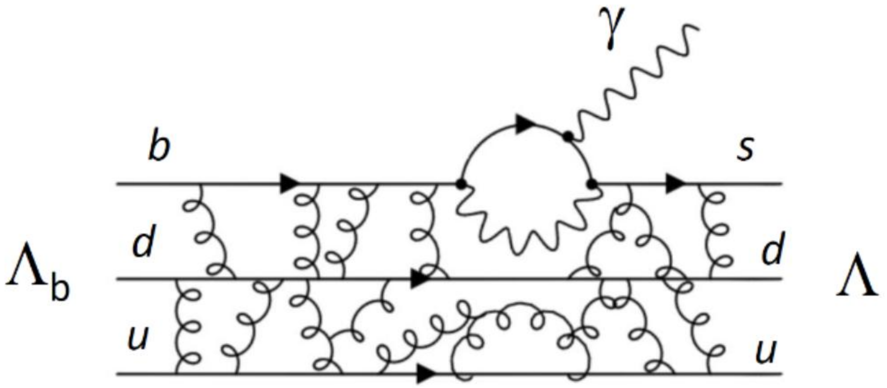
Ratio of cross section

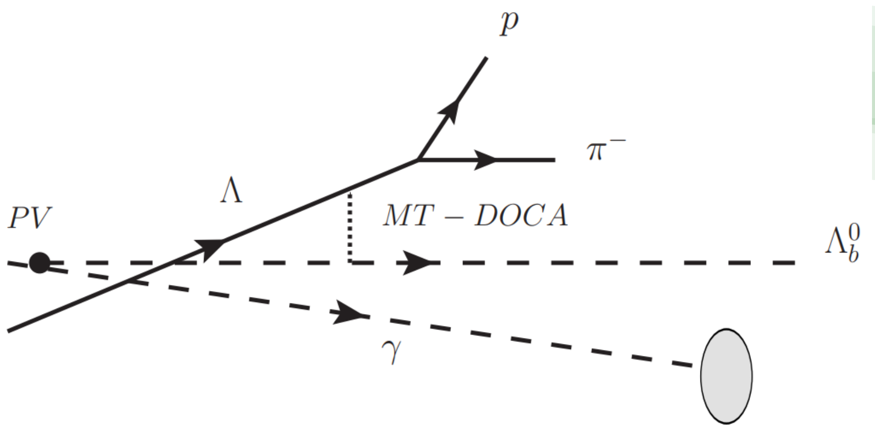
Statistical Systematic

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to K^-\pi^+\gamma)}{\mathcal{B}(\overline{B}^0 \to K^-\pi^+\gamma)} = \frac{N(B_s^0 \to K^-\pi^+\gamma)}{N(\overline{B}^0 \to K^-\pi^+\gamma)} \frac{\varepsilon(\overline{B}^0 \to K^-\pi^+\gamma)}{\varepsilon(B_s^0 \to K^-\pi^+\gamma)} \Big/ \frac{f_s}{f_d} = (3.2 \pm 1.1 \pm 0.3) \times 10^{-2}$$

$\Lambda_b^0 \rightarrow \Lambda^0\gamma$ branching fraction

- First observation of the decay $\Lambda_b^0 \rightarrow \Lambda^0\gamma$ was published using the 2016 Run 2 data corresponding to 1.7 fb^{-1}





- Combination of a long-lived particle (Λ^0) and a photon
  Challenging reconstruction

  Dedicated strategy → HLT2 and offline reconstruction

2016 branching fraction analysis https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.031801

2015-2018 Angular analysis https://journals.aps.org/prd/abstract/10.1103/PhysRevD.105.L051104

$\Lambda_b^0 \rightarrow \Lambda^0\gamma$ branching fraction

- Result in agreement with SM

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\gamma) = (7.1 \pm 1.5\,(\text{stat}) \pm 0.9\,(\text{syst})) \cdot 10^{-6}$$

Dominated by External fragmentation fractions
And Data simulation agreement

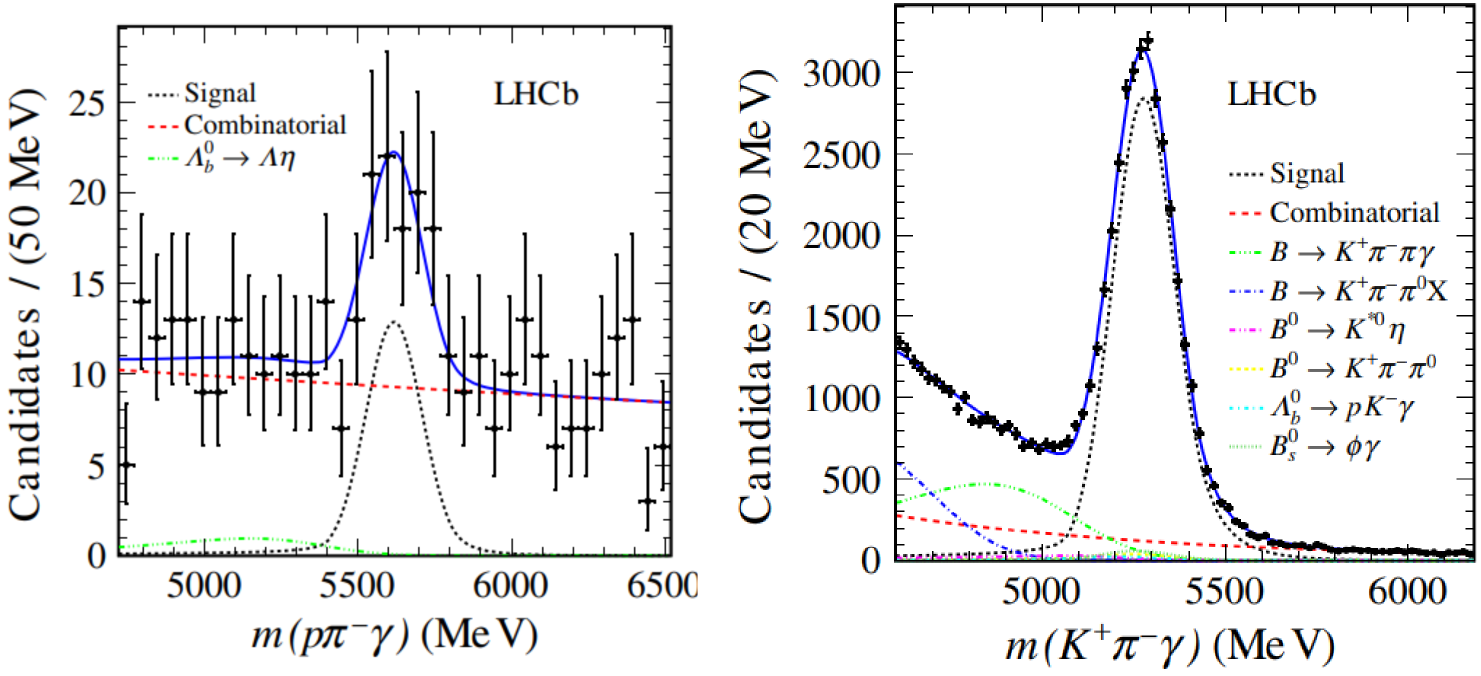
<u>Predictions from theory:</u>

$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda^0\gamma) = (7.3 \pm 1.5\,) \times 10^{-06}$

LCSR https://arxiv.org/pdf/0804.0648.pdf

$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda^0\gamma) = (7.1 \pm 3.4) \times 10^{-06}$

SU(3) Flavor Symmetry (IRA)
https://arxiv.org/pdf/2008.06624.pdf



https://doi.org/10.1103/PhysRevLett.123.031801

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

On going:

- Extend to 2017 and 2018 data ⟶ 5.4 fb^{-1}(Increase by factor of 3)
  ⟶ Precise measurement

- Normalisation channel $B^0 \to K^{*0}\gamma$

ratio of yields

combined reconstruction and selection efficiency

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

ratio of hadronization fractions

$B^0 \to K^{*0}\gamma$ is the most precise measurement of the possible normalisation modes

$\Lambda_b^0 \rightarrow \Lambda^0\gamma$ branching fraction

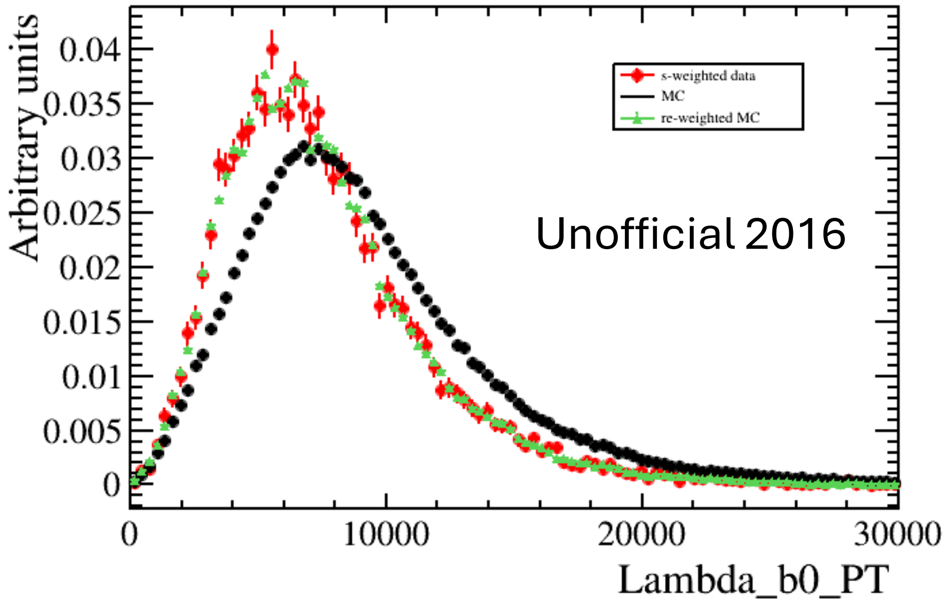
Selection process

- Trigger (dedicated Line) + stripping + preselection

- Control mode $\Lambda_b^0 \rightarrow pK^- J/\psi$

$\Lambda_b^0 p, \Lambda_b^0 p_t$ corrections are applied to the $\Lambda_b^0 \rightarrow \Lambda^0\gamma$ MC

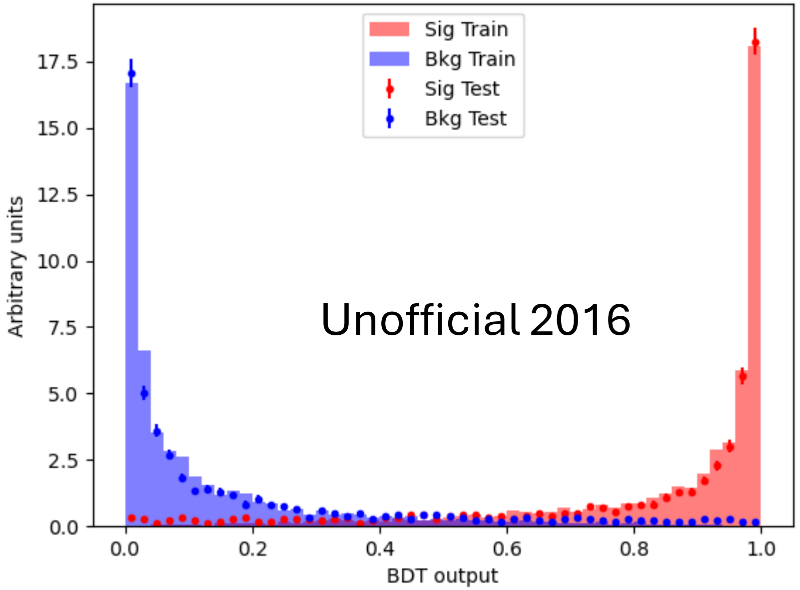
Splot technique with control mode



- BDT after a preselection

Signal → Reweighted simulated data

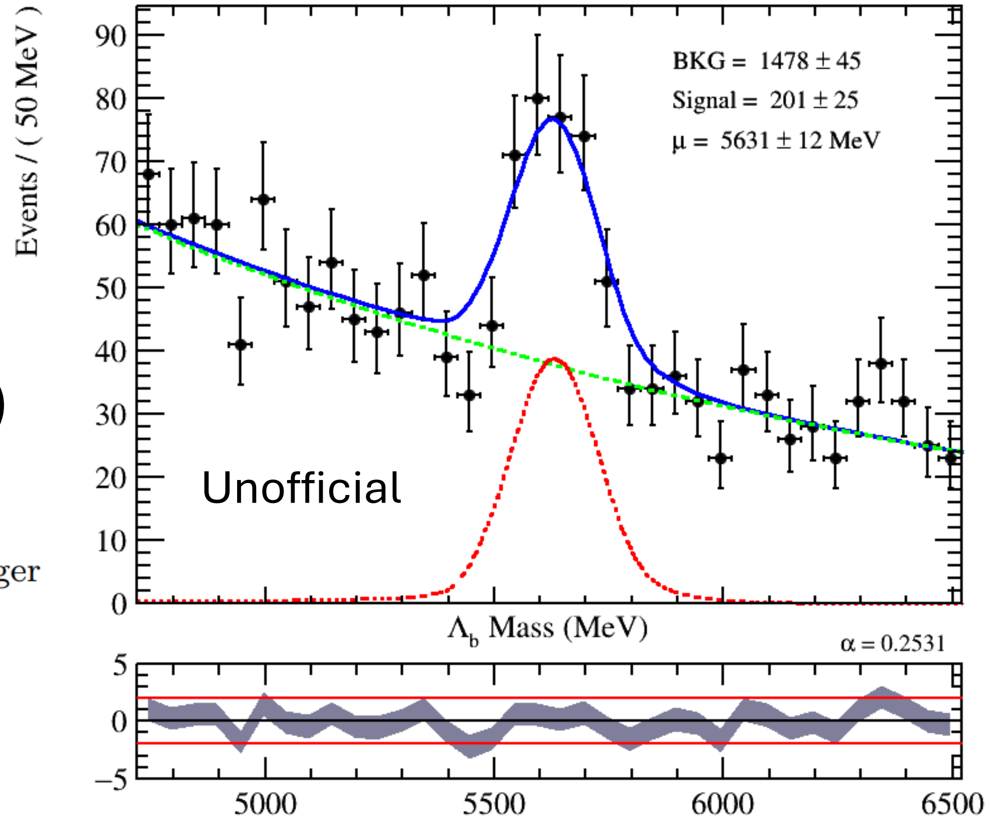
Background → Data in high side band



$\Lambda_b^0 \rightarrow \Lambda^0\gamma$ branching fraction

- Invariant mass fit of $\Lambda_b^0 \rightarrow \Lambda^0\gamma$

Preliminary results for 2016+2017+2018



In progress:

- Background studies ($\Lambda_b^0 \rightarrow \Lambda^0\gamma$ and $B^0 \rightarrow K^{*0}\gamma$)
- Efficiencies

$$\epsilon^{\text{sel}} = \epsilon^{\text{gen}} \times \epsilon^{\text{reco,strip}} \times \epsilon^{\text{presel}} \times \epsilon^{\text{tr PID}} \times \epsilon^{\text{BDT}} \times \epsilon^{\gamma\ \text{PID}} \times \epsilon^{\text{trigger}}$$

- Hadronisation factors

$$f_{\Lambda_b^0}/(f_d + f_u)\ (\Lambda_b^0\ p_{\text{T}}) = A[p_1 + \exp(p_2 + p_3 p_{\text{T}})]$$

- Systematic uncertainties

From the fit model + From normalization constant

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

Summary and prospects

- LHCb is an excellent laboratory to study b-hadron radiative decays
- Radiative decays offer a unique environment to look for BSM physics
- Many analyses using Run 1 and Run 2 (9 fb^{-1}) currently ongoing at LHCb

statistical uncertainty

- Run 3 data taking **> 20** $\boldsymbol{fb^{-1}}$

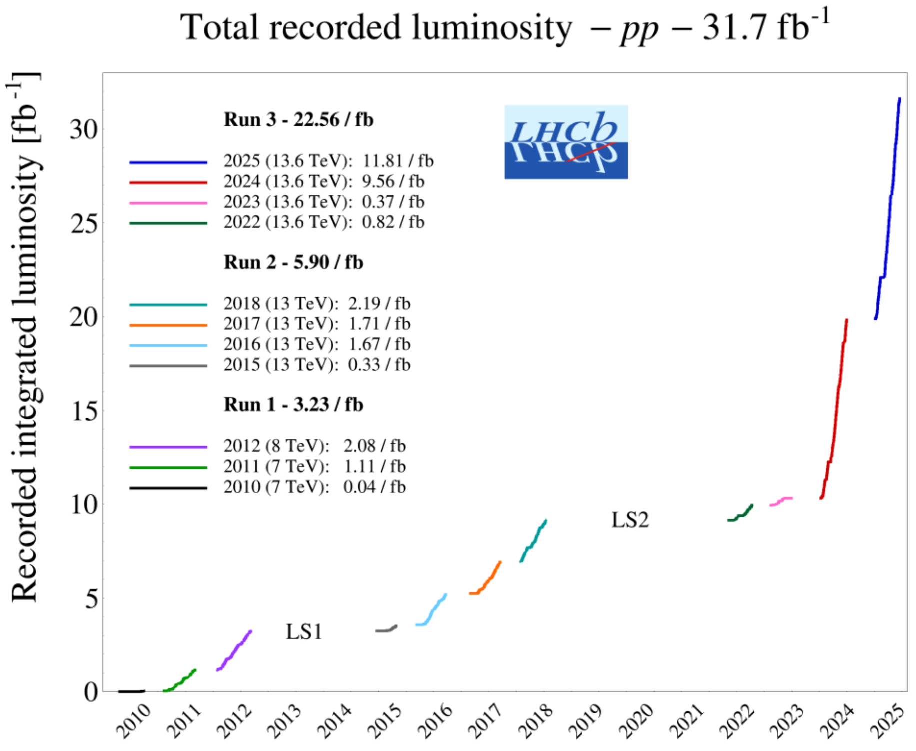
Upgraded detector with fully software-based trigger system

- Future Run 4 and Run 5 (target **300** $\boldsymbol{fb^{-1}}$):

Fully new detector to exploit flavour physics potential

Upgrade II: Improved granularity in ECAL

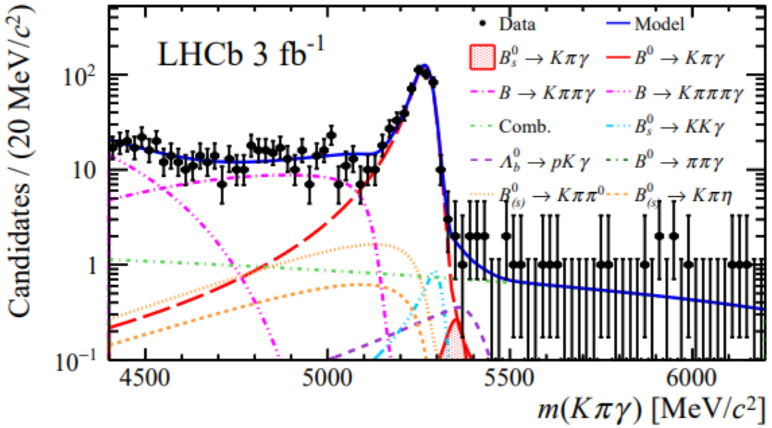
and Precise timing information



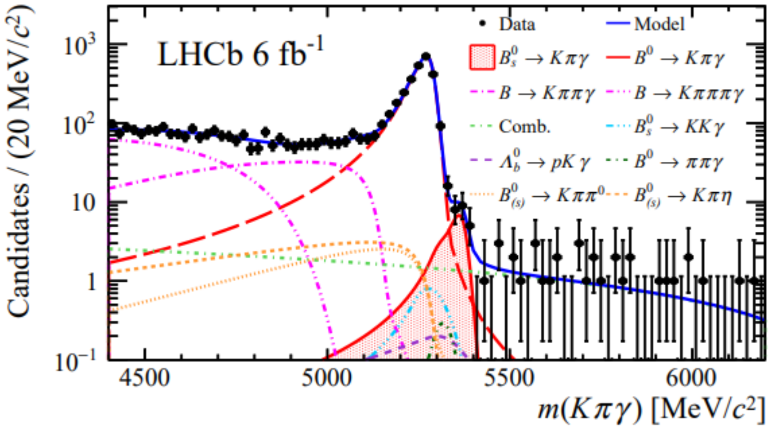
Thank you

Backup

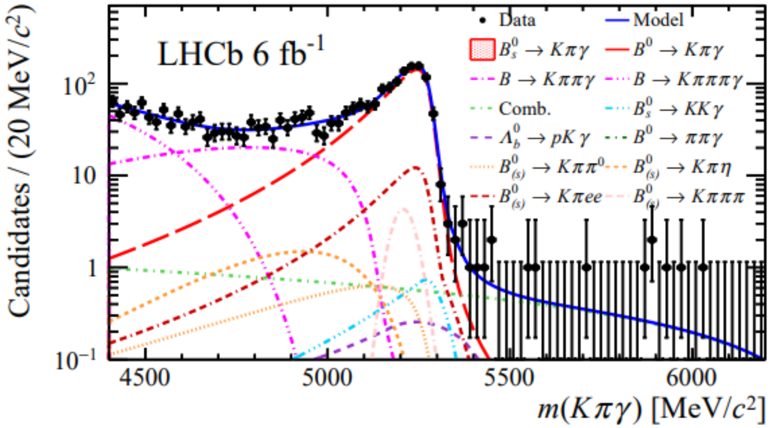
Search for the $B_s^0 \to K^-\pi^+\gamma$ decay with converted photons



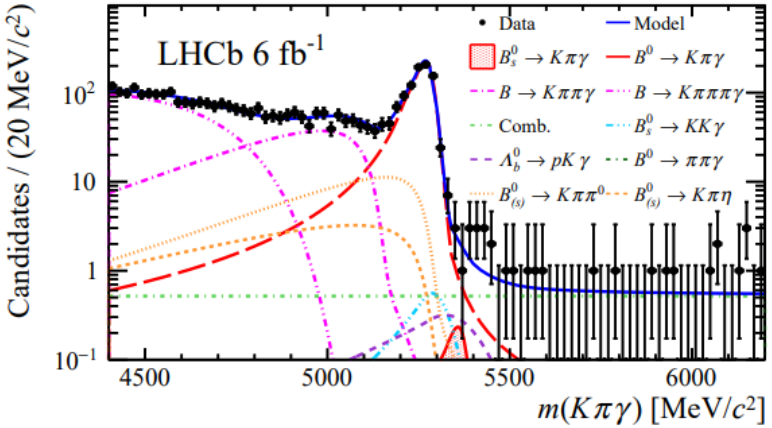
Run 1 downstream low-m$(K^-\pi^+)$



Run 2 downstream low-m$(K^-\pi^+)$



Run 2 long low-m$(K^-\pi^+)$



Run 2 downstream high-m$(K^-\pi^+)$

- 38 ± 18 signal decays
  (32 ± 11 Run 2 downstream low-m$(K^-\pi^+)$)
- In agreement with SM predictions
- **3.5 standard deviations significance**

Ratio of cross section

Statistical | Systematical

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to K^-\pi^+\gamma)}{\mathcal{B}(\bar{B}^0 \to K^-\pi^+\gamma)} = \frac{N(B_s^0 \to K^-\pi^+\gamma)}{N(\bar{B}^0 \to K^-\pi^+\gamma)} \frac{\varepsilon(\bar{B}^0 \to K^-\pi^+\gamma)}{\varepsilon(B_s^0 \to K^-\pi^+\gamma)} / \frac{f_s}{f_d} = (3.2 \pm 1.1 \pm 0.3) \times 10^{-2}$$

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

Selection process of control mode $\Lambda_b^0 \to \Lambda^0\gamma$

Trigger:

- L0 Photon || L0 Electron
- Hlt2RadiativeLb2L0GammaLL
- Hlt1TrackMVA

Stripping:

- *Lb2L0Gamma*

Preselection:

Variable	$\Lambda_b^0 \to \Lambda J/\psi$	Units
Track χ^2/ndof	< 4	
π ProbNNpi	> 0.2	
p ProbNNp	> 0.2	
μ ProbNNmu	> 0.2	
Λ ΔM	< 6	MeV/c^2
Λ IP	> 0.15	mm
Λ χ^2_{IP}	> 16	
Λ χ^2_{FD}	> 225	
J/ψ ΔM	< 60	MeV/c^2
J/ψ χ^2_{Vtx}	< 16	
Λ_b^0 p_T	> 4000	MeV/c

Table 7: Selection for the $\Lambda_b^0 \to \Lambda J/\psi$ decay channel.

+ PID cuts

BDT input variables:

Variables
$\pi^\pm$ p_{T}
p p_{T} + $\pi^\pm$ p_{T} + γ p_{T}
p IP χ^2
$\pi^\pm$ IP
Tracks DOCA
γ p_{T}
Λ p_{T}
Λ IP
Λ IP χ^2
Λ FD
Λ_b^0 p_{T}
Λ_b^0 MTDOCA
Λ Cone(1.0) $\mathcal{A}_p$
Λ Cone(1.0) $\mathcal{A}_{p_{\text{T}}}$
γ Cone(1.0) $\mathcal{A}_{p_{\text{T}}}$