B Radiative decays at LHCb

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第4届LHCb前沿物理研讨会

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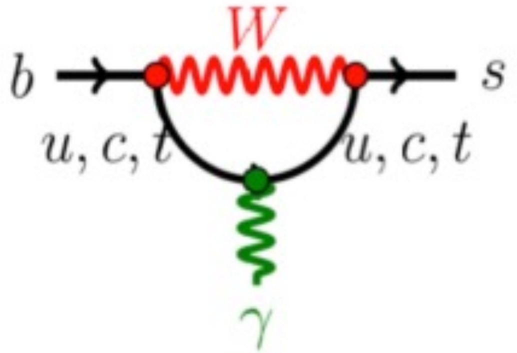
Outline

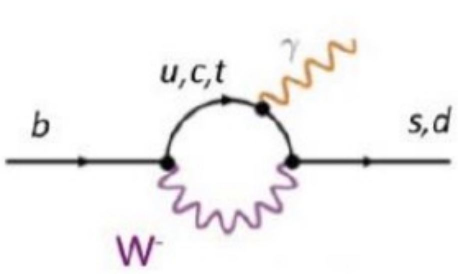
- Introduction
  - Radiative penguin and New Physics
  - Photon reconstruction at LHCb
- Published analysis
- Outlook

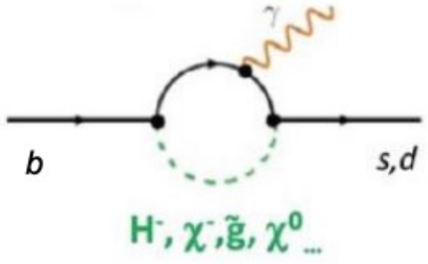
Radiative B Decays

- Radiative b-hadron decays correspond to $b \rightarrow q\gamma(q = d, s)$ transitions.

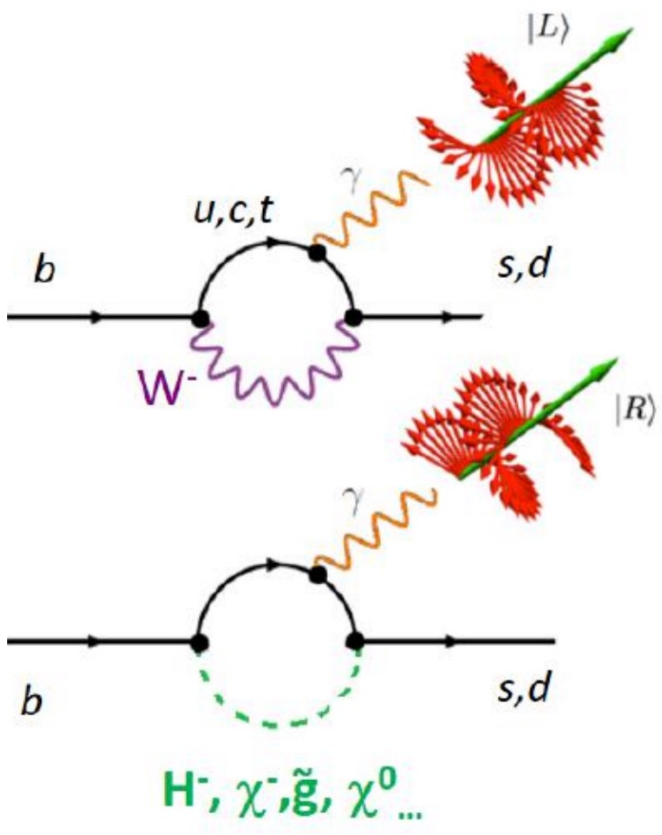


- Probes of New Physics
  - Rare decays: BR < 10^{-4}
  - CP asymmetries($b \rightarrow s, b \rightarrow d$)
  - measurements of the polarization of the photon emitted in the decay
  - NP at large energy scale can be probed indirectly by studying of penguin loop process.





Photon polarization asymmetry



- Photon polarization $\lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}$

- Described by an effective Hamiltonian

$$\mathcal{H}_{rad} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* (C_{7L} \mathcal{O}_{7L} + C'_{7R} \mathcal{O}'_{7R})$$

- In SM, the photon's polarization is predominantly left-handed. $\frac{C'_{7R}}{C_{7L}} = \frac{A_R(b_L \to s_R \gamma_R)}{A_L(b_R \to s_L \gamma_L)} \approx \frac{m_s}{m_b} = 0.02$

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

- The right-handed component could be enhanced in NP models.

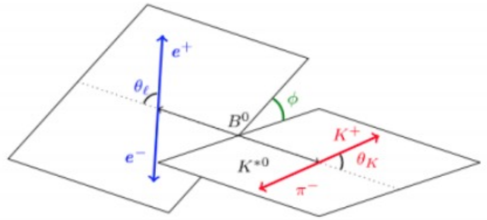
e.g. $\left|\frac{A_R}{A_L}\right|$ up to 0.5 [Atwood et al., PRL 79 (1997) 185-188] [Yu et al., JHEP 12 (2013) 102]

Photon polarisation

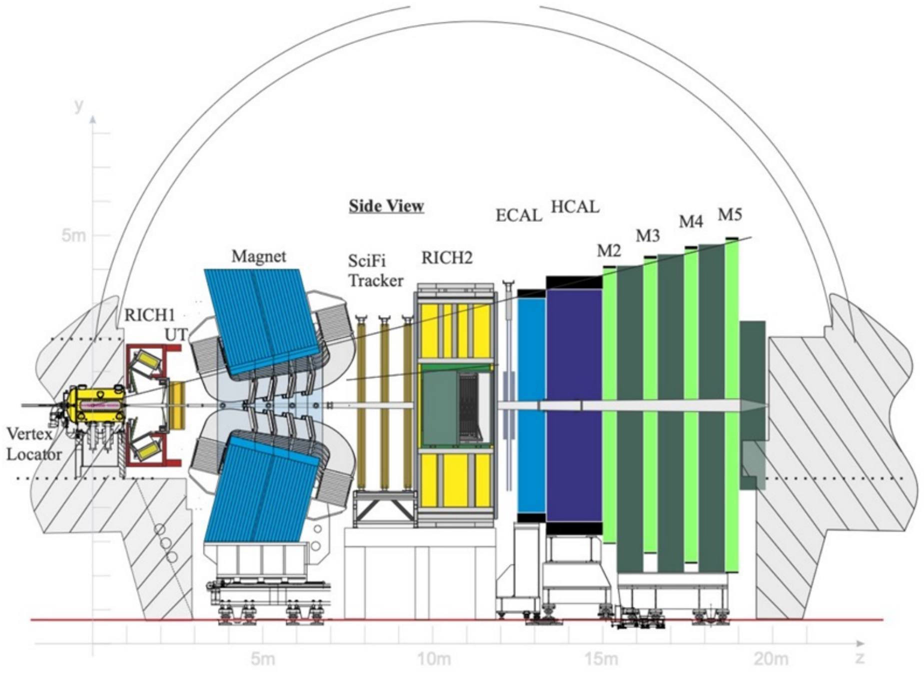
- Experimentally, the photon polarisation can be extracted from:

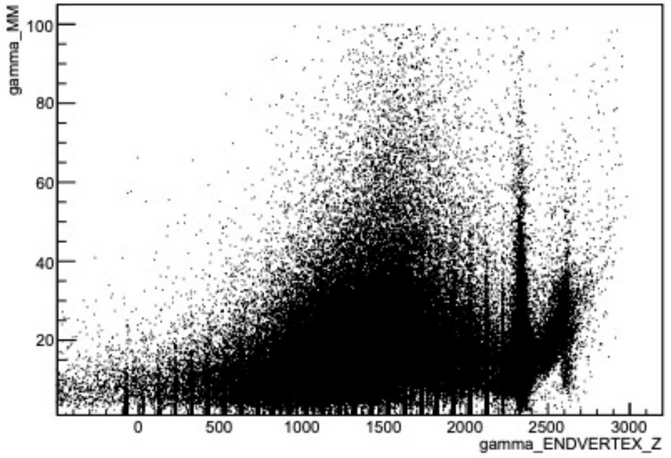
  - ➢ Angular/Amplitude analysis of radiative decays:

    e.g. $\mathrm{B}^{+} \to K^{+}\pi^{+}\pi^{-}\gamma$ (first observation photon polarised)
  - ➢ Time-dependent analysis, e.g. $B_s^0 \to \phi\gamma, B^0 \to K_s\pi^{+}\pi^{-}\gamma$
    - CPV parameters S and A^{Δ} are sensitive to C_7 and C_7'
  - ➢ Angular analysis of b-baryon radiative decays, e.g. $\Lambda_b \to \Lambda\gamma$, $\Xi_b \to \Xi\gamma$
    - Spin 1/2 b-baryons compared to spinless B meson.
  - ➢ Low q^2 virtual photon in $\mathrm{B}^0 \to K^{*0}e^{+}e^{-}$
    - Dominate by $b \to s\gamma$ pole at low q^2



Photon reconstruction





Converted photon vertex

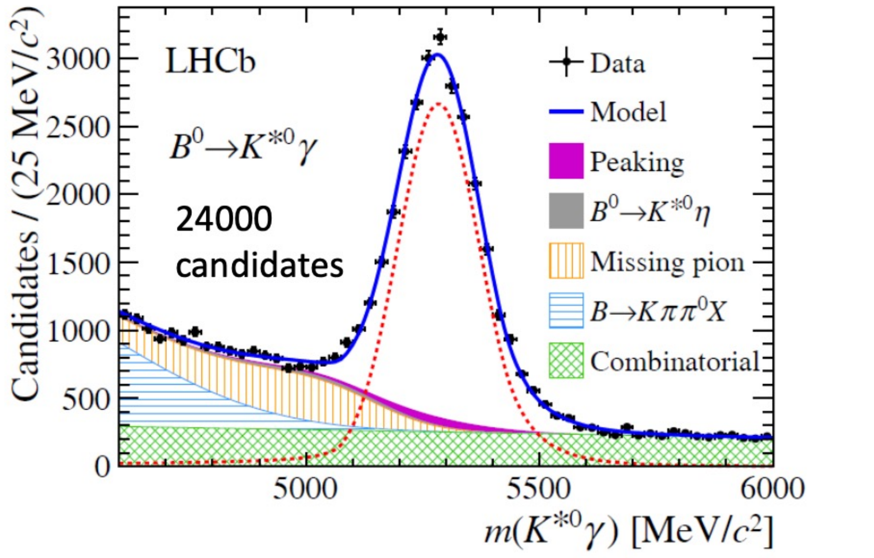
[LHCb-INT-2015-040]

- Calorimeter photon: energy deposits in the Electromagnetic Calorimeter

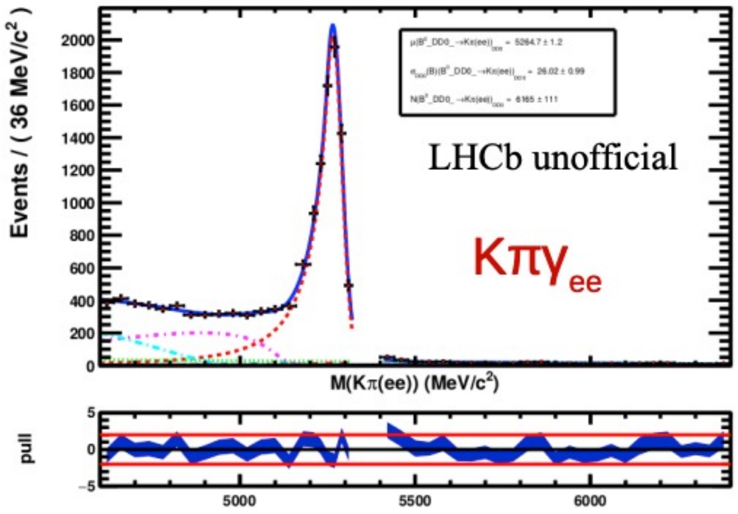
- Converted photon: $\gamma \rightarrow e^{+}e^{-}$
  - Better mass resolution
  - Lower efficiency than the Calorimeter photon(5-10%)

- Hardware Trigger constraints(L0 Photon)
  - ET> 2.5 or 3 GeV
  - Efficiency ~ 30%-40%

- Challenging in radiative decays analysis:
  - ➢No constrains on vertexing from photon (calo photon)
  - ➢Large photon multiplicity (large background)
  - ➢Mass resolution (due to the photon reconstruction)



[PRL 118, 021801 (2017)]

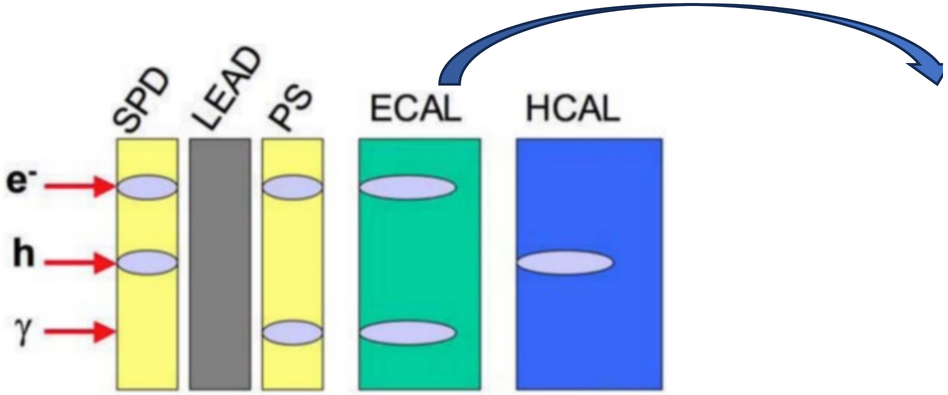


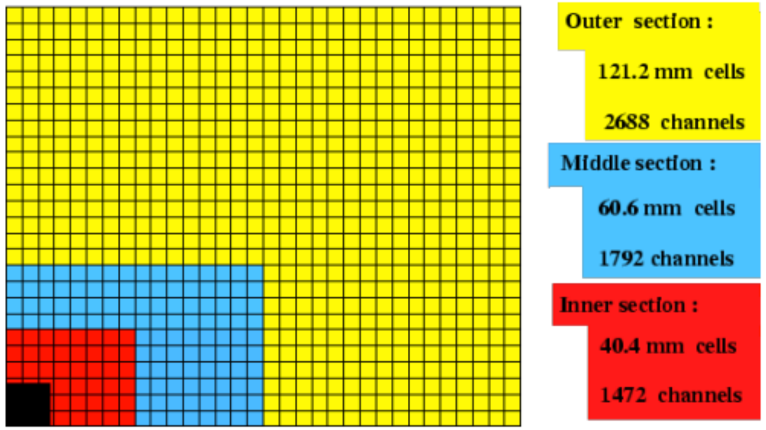
Neutral particles identification at LHCb

- Rely on calorimetry to identify photons, high-energy neutral pions, and electrons

- Photons and high momenta π^0 are hard to distinguish($\pi^0 \to \gamma\gamma$)

- 14 variables(listed in the table) and 3 different Neural Networks are trained
  - Shape, energy deposited, number of hits. [tool for γ/π0 separation at high energies](LHCb-PUB-2015-016)

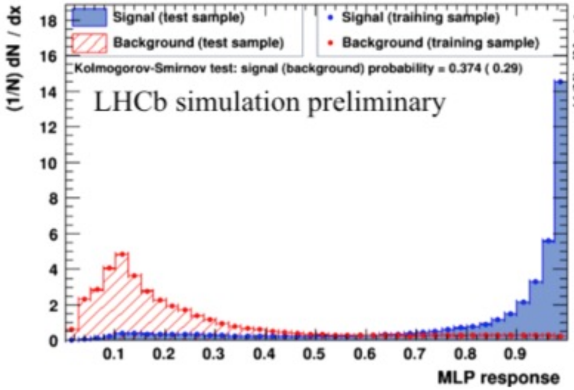




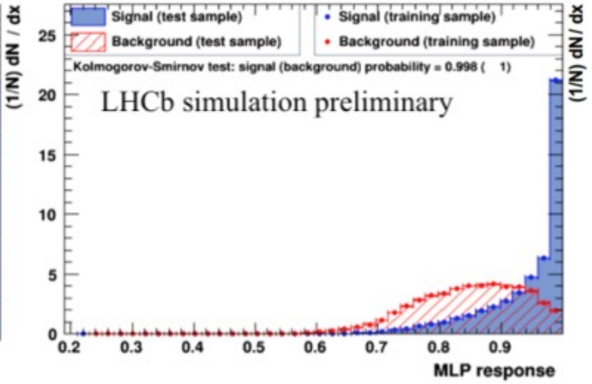
➢MLP outputs:

- Photon/hadron separation – “IsNotH”
- Photon/electron separation – “IsNotE”
- Photon/π0 separation – “IsPhoton”

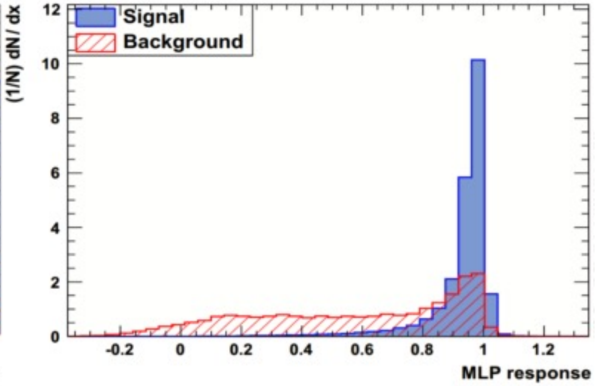
IsNotH

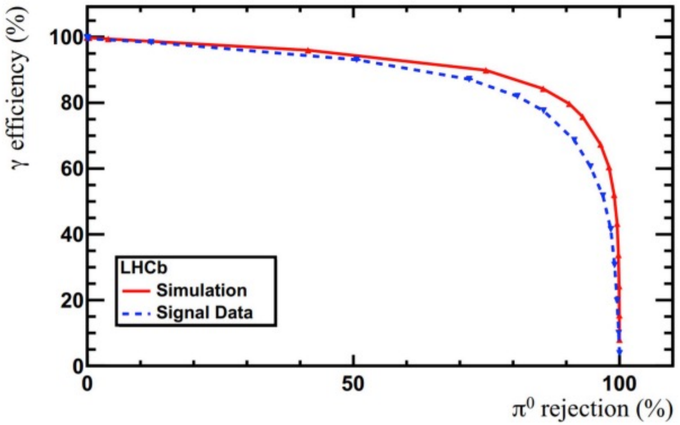


IsNotE



IsPhoton [2]





IsPhoton > 0.6

	ϵ_{sig}	ϵ_{bkg}
Inner	0.97	0.52
Middle	0.98	0.55
Outer	0.98	0.57

[tool for γ/π0 separation at high energies](LHCb-PUB-2015-016)

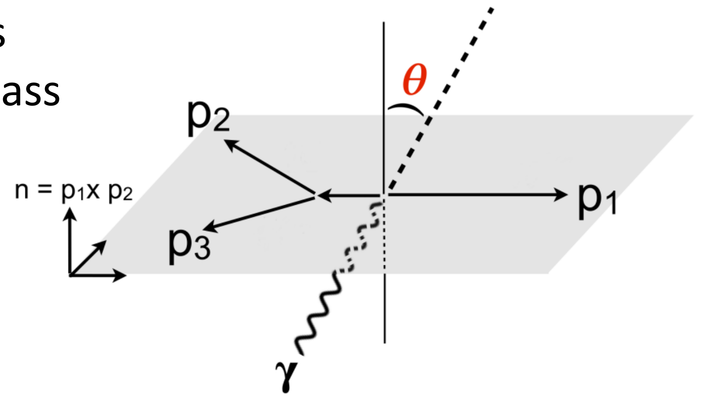
[PRL 112, 161801 (2014)]

$B^+ \to (K_{res})K^+\pi^+\pi^-\gamma$

- BR measurement: $(27.6 \pm 2.2)\times 10^{-6}$(Belle) [Phys. Rev. Lett. 89, 231801]
- The photon polarization can be inferred from the polarization of the K resonance.

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

depend on the resonances present in the $K^+\pi^+\pi^-$ mass region.



- In the $\overline{K}_{res}$ rest frame

  Define an up-down asymmetry

$$A_{ud} = \frac{\int_0^1 d\cos\hat{\theta}\frac{d\Gamma}{d\cos\hat{\theta}} - \int_{-1}^0 d\cos\hat{\theta}\frac{d\Gamma}{d\cos\hat{\theta}}}{\int_{-1}^1 d\cos\hat{\theta}\frac{d\Gamma}{d\cos\hat{\theta}}} = C\lambda_\gamma$$

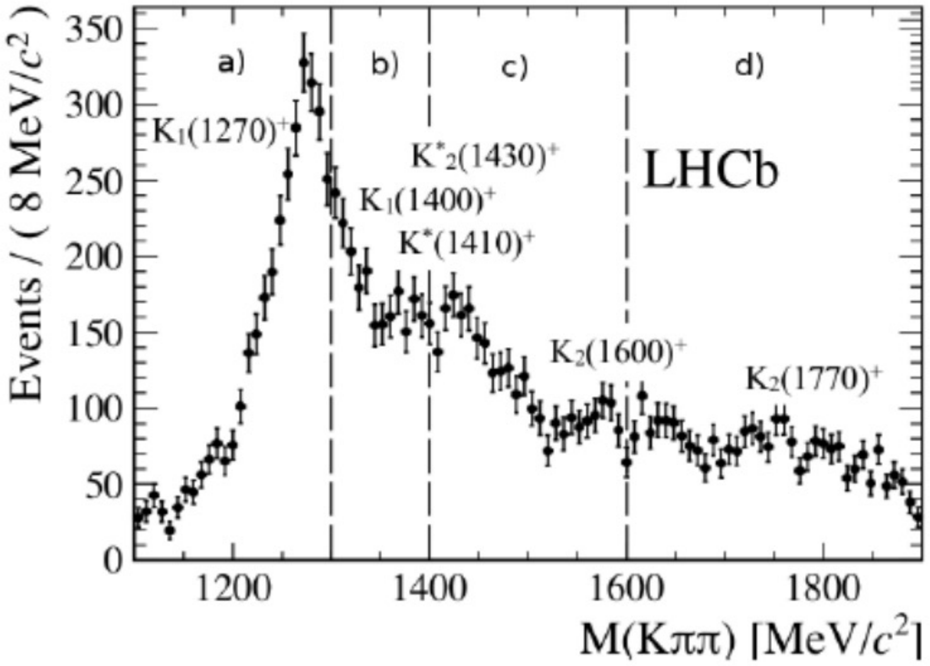
[Phys. Rev. D 66, 054008]

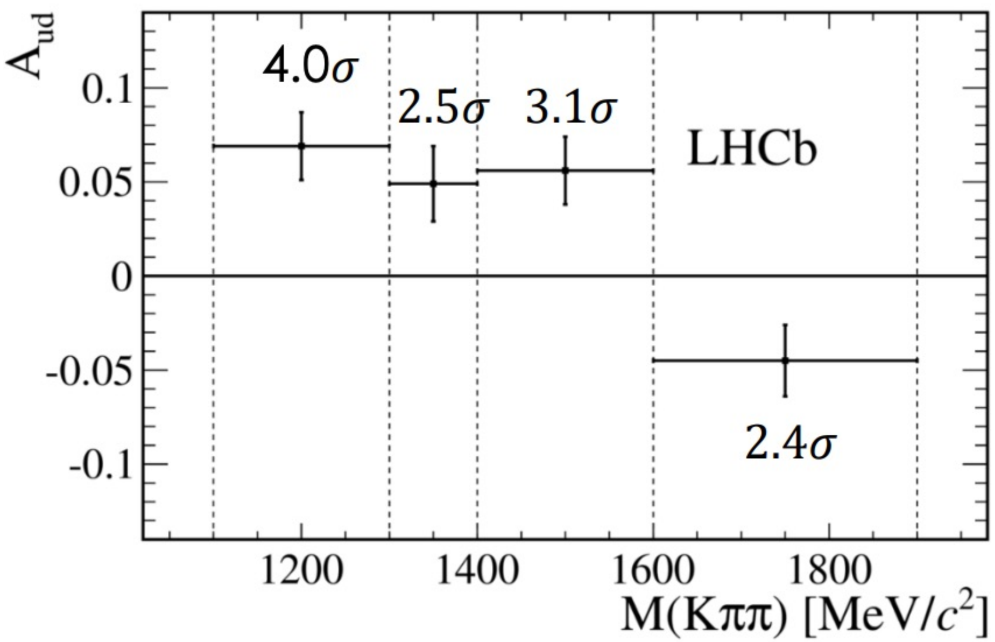
- C is related to $K\pi\pi$ resonance and interference related

[PRL 112, 161801 (2014)]

$B^+ \to (K_{res})K^+\pi^+\pi^-\gamma$

- First observation of photon polarization
  - Using Run1 data(3 fb^{-1})
  - ~14k candidates with all intermediate resonances of $[K\pi\pi]$in [1.1, 1.9] GeV/c^2 mass range.





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

[PRL 123, 081802 (2019)]

$B_s^0 \to \phi\gamma$

- Direct access to the photon polarisation through the time-dependent decay rate

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

- The coefficients S and A^{Δ} are sensitive to C_7 and C_7'

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

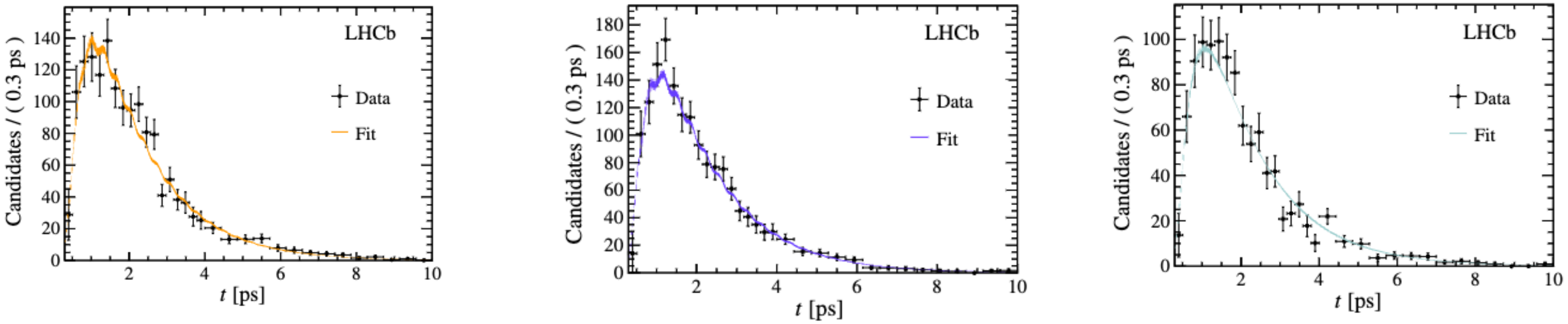
$$\mathcal{S}_{\phi\gamma} \simeq \frac{2\,\mathrm{Im}\left(e^{-i\phi_s} C_7 C_7'\right)}{|C_7|^2 + |C_7'|^2},$$

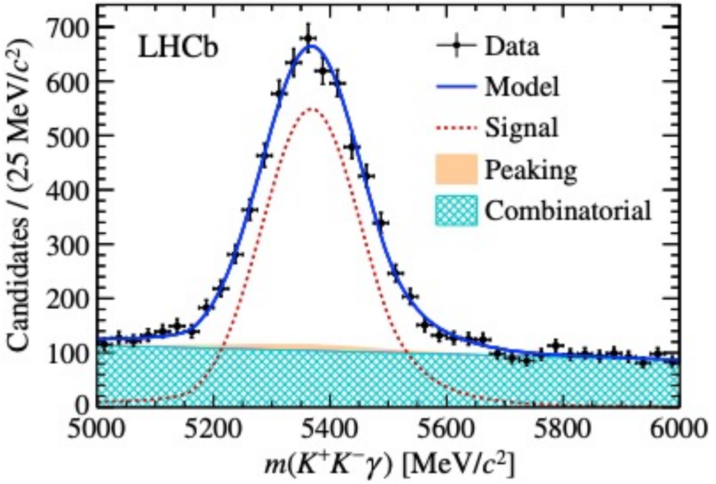
- Run1 data(3 fb^{-1}), 5.1K candidates
- Measurement results

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

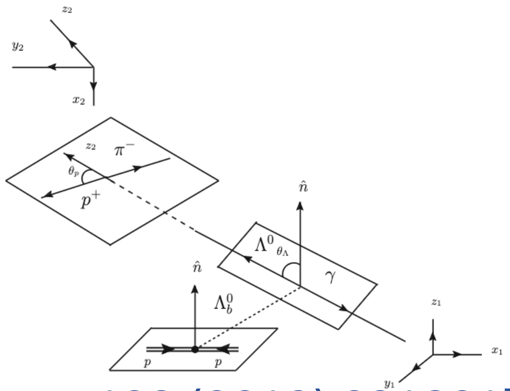
$$\mathcal{S}_{\rm SM} = 0 \pm 0.002,$$
$$\mathcal{C}_{\rm SM} \simeq 0.005 \pm 0.005,$$
$$\mathcal{A}^{\Delta}_{\rm SM} = 0.047^{+0.029}_{-0.025},$$

Compatible with SM expectation within 1.3σ, 0.3σ, 1.7σ





[Phys. Rev. D105 (2022) L051104]



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

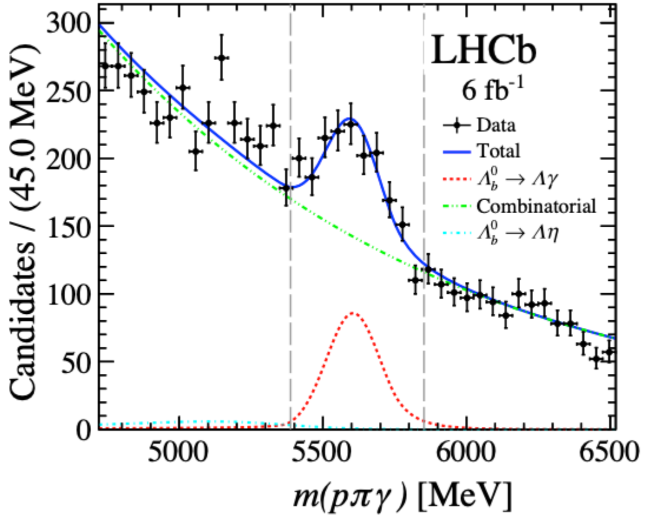
- First angular analysis of radiative b-baryon decays
  - Follows the first observation of (65 ± 13) events in 2016 data [Phys. Rev. Lett. 123 (2019) 031801]
  - $B(\Lambda_b^0 \to \Lambda\gamma)$ = (7.1 ± 1.5) x10^{-6} $\quad \alpha_\gamma \equiv \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R}$
- Extract γ-polarization (α_γ) from proton helicity angle θ_p (Eur. Phys. J. C 79 (2019) 634)
  - α_Λ: $\Lambda \to p\pi^-$ weak decay parameter (BESIII input)

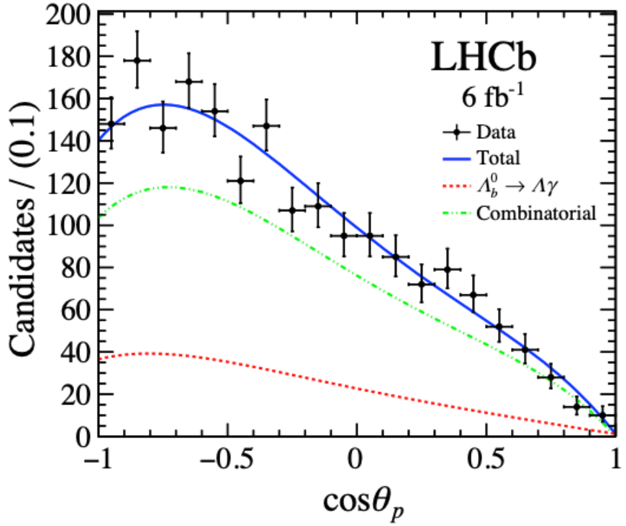
$$\frac{d\Gamma}{d(\cos\theta_p)} \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p$$

- Run2(6fb^{-1}), ~440 candidates
- Results

$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\,(\text{stat.})^{+0.04}_{-0.13}\,(\text{syst.})$$

Compatible with the SM prediction!



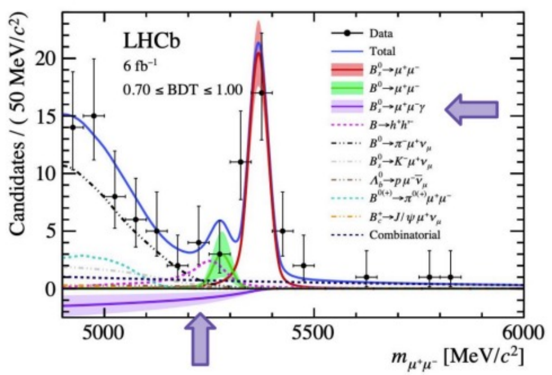


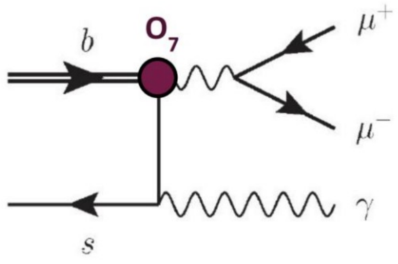
JHEP 07 (2024) 101

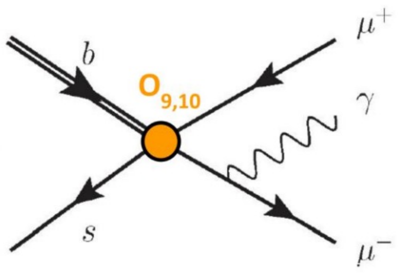
$B_s^0 \to \mu\mu\gamma$

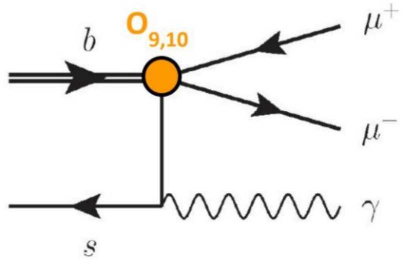
- SM BR prediction: low $q^2 (8.3 \pm 1.3) \times 10^{-9}$,
  high $q^2 (8.90 \pm 0.98) \times 10^{-10}$
- First directly searching at low q^2
  - Indirect methods(prob as the background of $B_s^0 \to \mu\mu$) BR < $(2.0 \pm 1.3) \times 10^{-9}$
- Offer a sensitivity to $C'_{9,10}$ and C'_7

Phys. Rev. D 105 (2022) 012010 184









[JHEP 07 (2024) 101]

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

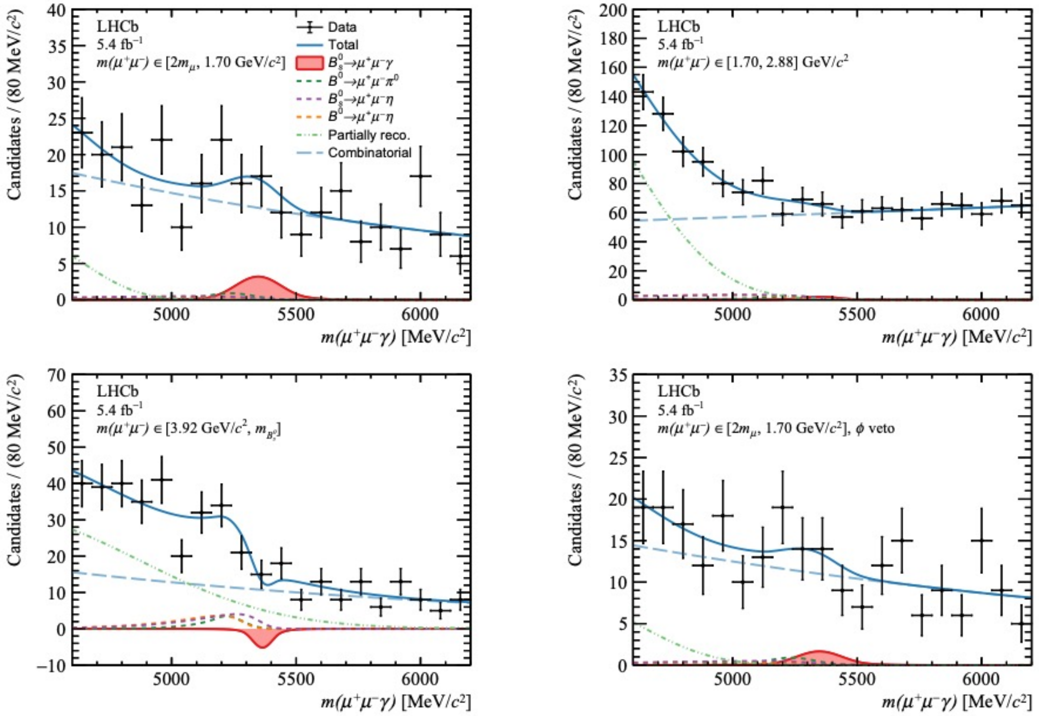
- Strategy
  - Using 5.4 fb^{-1} of Run2 data
  - Performed in 3 dimuon mass bins

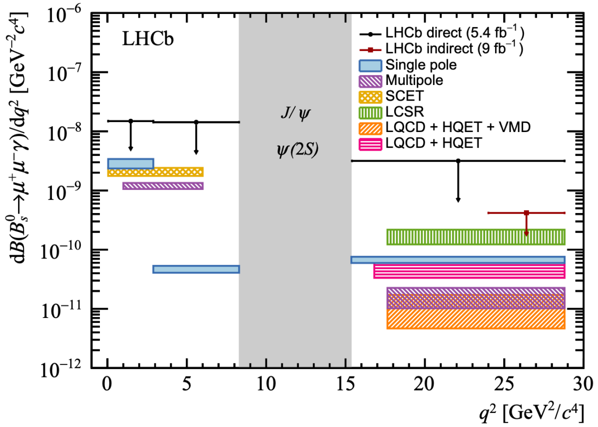
I. Low-q² : m(μμ) < 1.7 GeV/c²
II. Middle-q² : 1.7< m(μμ)(GeV/c²) < 2.88
III. High-q² : m(μμ) > 3.92 GeV/c²

- Result: no significant signal

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 4.2 \times 10^{-8},\ m(\mu^+\mu^-) \in [2m_\mu,\ 1.70]\ \mathrm{GeV}/c^2,$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 7.7 \times 10^{-8},\ m(\mu^+\mu^-) \in [1.70,\ 2.88]\ \mathrm{GeV}/c^2,$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 4.2 \times 10^{-8},\ m(\mu^+\mu^-) \in [3.92,\ m_{B_s^0}]\ \mathrm{GeV}/c^2,$$

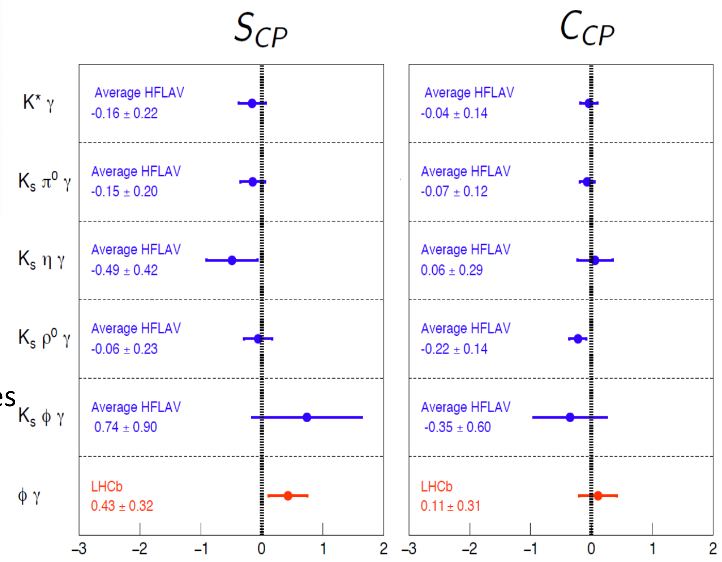
- Consistent with all SM predictions





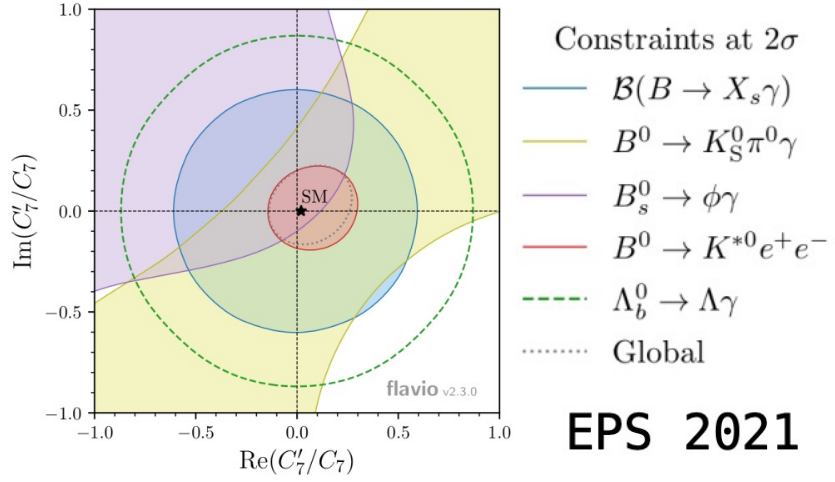
Analysis	dataset	Paper
Search for the radiative $\Xi_b^- \to \Xi^- \gamma$decay	Run 2	JHEP 62 (2022)
Strong constraints on the $b \to s\gamma$ photon polarisation from $B \to K^* ee$ decays	Run 1+2	JHEP 12 (2020) 081
Study of tagged $B_s \to \phi\gamma$ decays	Run 1	Phys. Rev. Lett. 123 (2019) 081802
First observation of $\Lambda_b \to \Lambda^0\gamma$ decays	2016	Phys. Rev. Lett. 123 (2019) 031801
Accessing the photon polarization in $B_s \to \phi\gamma$ decays	Run 1	Phys. Rev. Lett. 118 (2017) 021801
Search for the rare decays $B^0 \to J/\psi\gamma$ and $B_s^0 \to J/\psi\gamma$	Run 1	Phys. Rev. D 92 (2015) 11
Angular analysis of $B \to K^* ee$	Run 1	J. High Energ. Phys. 04 (2015) 64
Observation of photon polarization in $B^\pm \to (K^\pm\pi^\mp\pi^\pm)\gamma$	Run 1	Phys. Rev. Lett. 112 (2014) 161801
Measurement of $BR(B_d \to K^{*0}\gamma)/BR(B_s \to \phi\gamma)$ and $A_{CP}(B_d \to K^{*0}\gamma)$	2011	Nucl. Phys. B867 (2013) 1
Measurement of $BR(B_d \to K^{*0}\gamma)/BR(B_s \to \phi\gamma)$	0.37 1/fb (2011)	Phys. Rev. D 85 (2012) 112013

Competitive with previous measurements from B-factories



[PRL 123, 081802 (2019)]

Amplitude analsysis of the $B_s^0 \to K^+K^-\gamma$ decay	LHCb-PAPER-2024-002	2406.00235	JHEP
Search for $B_s^0 \to \mu^+\mu^-\gamma$ decay	LHCb-PAPER-2023-045	2404.03375	JHEP 07 (2024) 101
Amplitude analysis of the $\Lambda_b \to pK^-\gamma$ decay	LHCb-PAPER-2023-036	2403.03710	JHEP 06 (2024) 098
Measurement of the photon polarization in $\Lambda_b^0 \to \Lambda\gamma$ decays	LHCb-PAPER-2021-030	2111.10194	Phys. Rev. D105 (2022) L051104



EPS 2021

$$\mathcal{B}(\Xi_b^- \to \Xi^-\gamma) < 1.3 \times 10^{-4}$$ 95%CL

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$

What's next

$$\frac{\mathcal{B}(B^0 \to \rho^0\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2$$

- Suppressed modes
  - ➢ $B^0 \to \rho^0\gamma$(expected 1000)
    - Optimization cross-feed backgrounds($K\pi$, KK, $p\pi$), combinatorics(BDT)
  - ➢ $B_s^0 \to K^*\gamma$ and $B_s^0 \to \phi\gamma$ with converted photons(better B mass resolution)

- Several final-states still to be explored (3hγ, 4hγ)
  - ➢ Other 3hγ or 4hγ systems be more advantageous than $K\pi\pi\gamma$
- Run3 statistics will boost all statistically limited analysis

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%

- CCNU ongoing radiative decay analysis
  - ➢ Searching for $\mathrm{B}_{(s)}^0 \to 4h\gamma$
  - ➢ TD-CPV analysis of $\mathrm{B}^0 \to \pi\pi\gamma$
  - ➢ Searching for $\mathrm{B}_s^0 \to J/\psi\gamma$(converted photon,run1+run2)

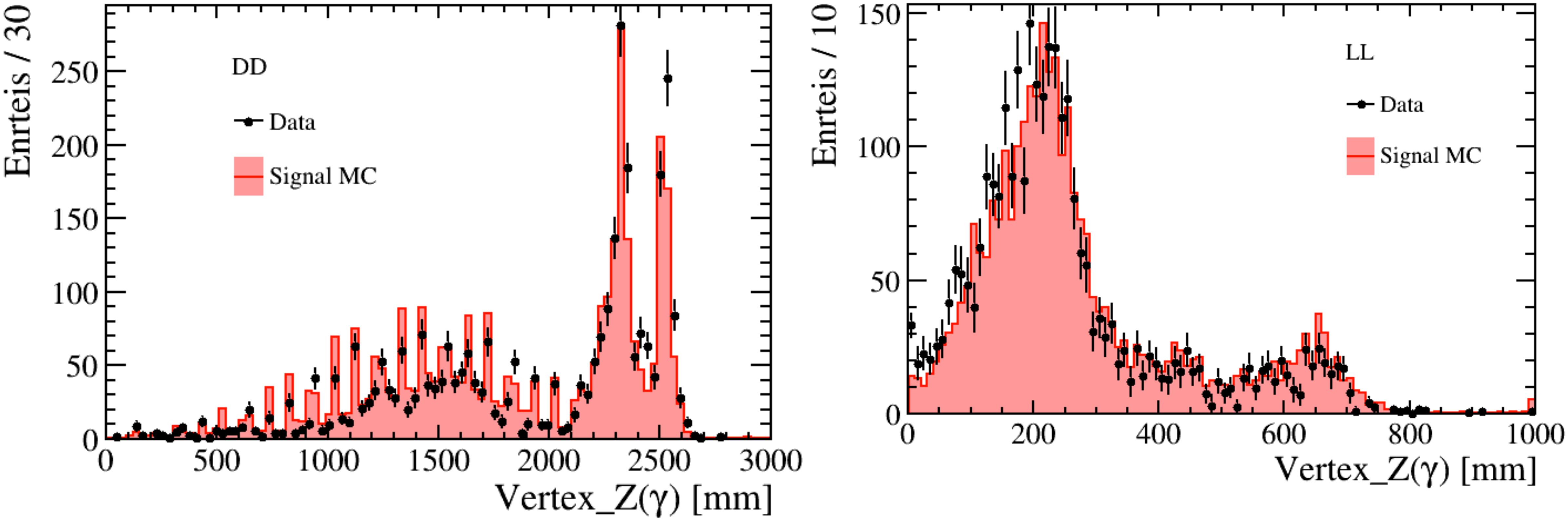
Summary

- Radiative b-decays allow probing NP.
- The photon polarization can be measured in several ways.
  - $B^+ \to (K_{res})K^+\pi^+\pi^-\gamma$: First direct observation of a non-zero photon polarization
  - TD-CPV $B_s^0 \to \phi\gamma$
  - b baryon radiative decay: $\Lambda_b^0 \to \Lambda\gamma$
  - Direct searching for $B_s^0 \to \mu\mu\gamma$
- More results in the future about the B radiative decay.

Thanks for listening

Backup

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

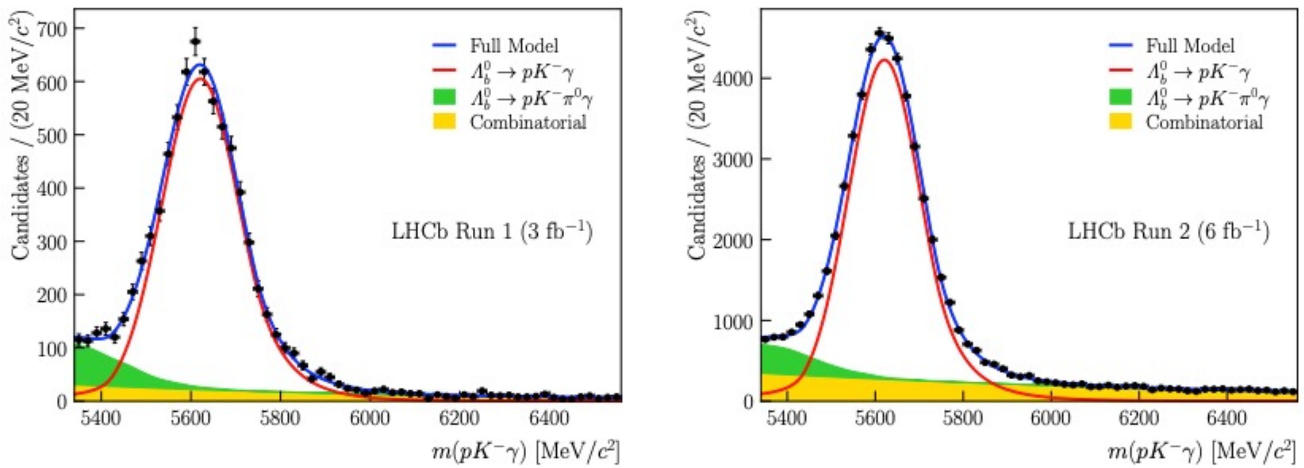


arXiv:2403.03710

$\Lambda_b^0 \to pK^-(\Lambda^*)\gamma$

$\Lambda_b^0 \to pK^- J/\psi$
arXiv:1507.03414

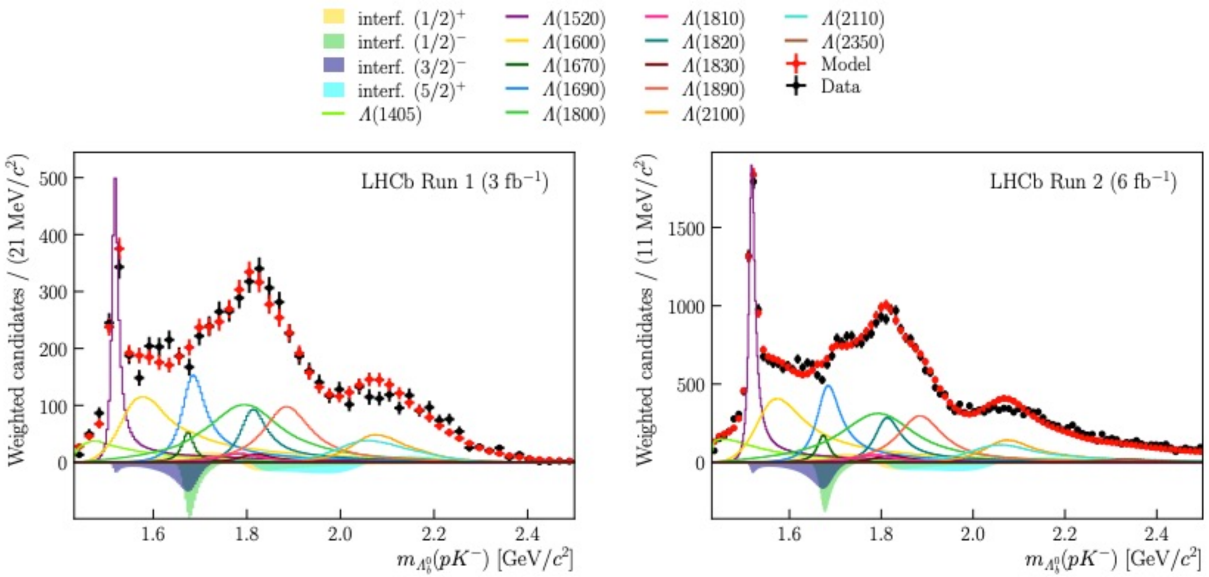
- Characterize the pK spectrum at the photon pole.
- Fully reconstructed in VELO, has Λ_b^0 vertex.
- Using Run1 an Run2 data
- 6855 ± 93(Run1) and 45558 ± 247(Run2) candidates

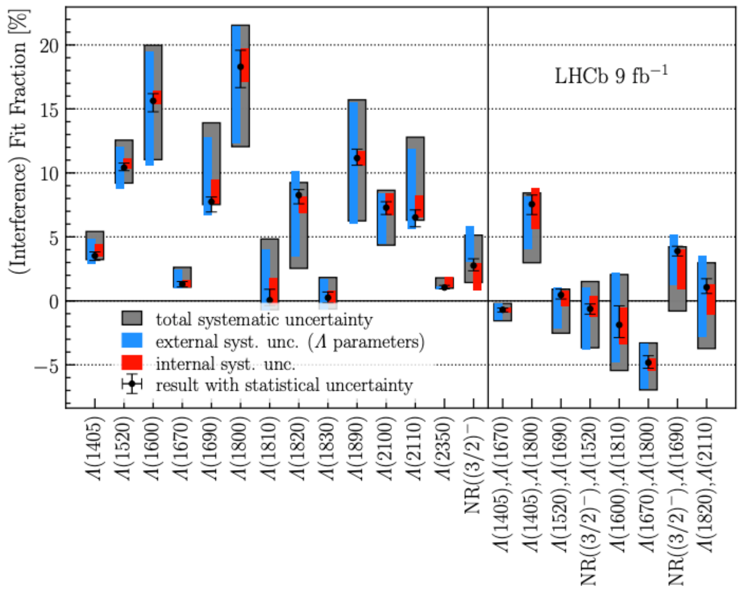


JHEP 06 (2024) 098

$\Lambda_b^0 \to pK^-(\Lambda^*)\gamma$

- $\Lambda(1800), \Lambda(1600), \Lambda(1890), \Lambda(1520)$ in $\Lambda_b^0 \to pK^-(\Lambda^*)\gamma$
- Largest interference involves $\Lambda(1405)$, $\Lambda(1800)$
- provides information about the pK^- spectrum to heavier Λ





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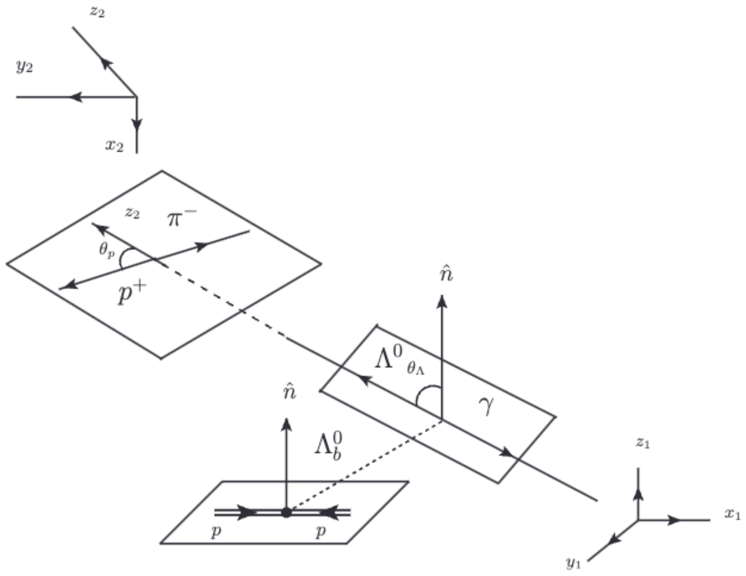
$\Lambda_b^0 \to \Lambda\gamma$

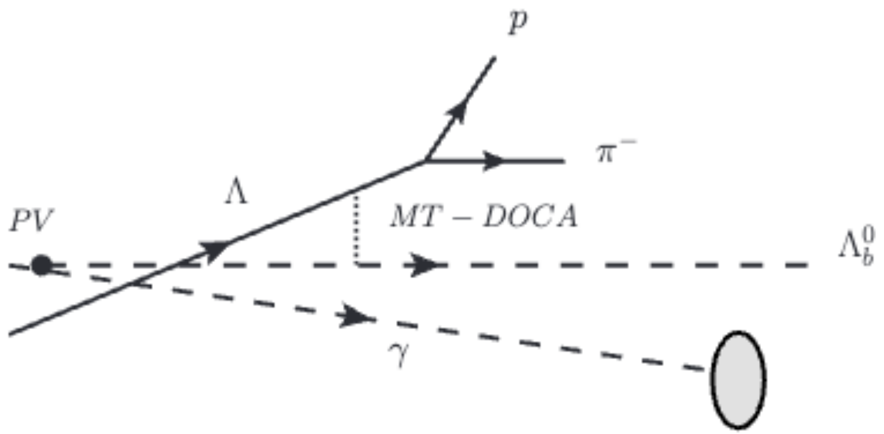
- SM prediction BR: $(0.06\sim1)\times10^{-5}$ [Eur. Phys. J. C59 (2009) 861, JHEP 12 (2011) 67, Commun. Theor. Phys. 58 (2012) 872, PRD 96 (2017) 053006]
- Using 2016 data(1.7 fb^{-1})
- Sensitivity to C_7' C_7 through angular distributions
- Used $B^0 \to K^{*0}\gamma$ as normalisation mode

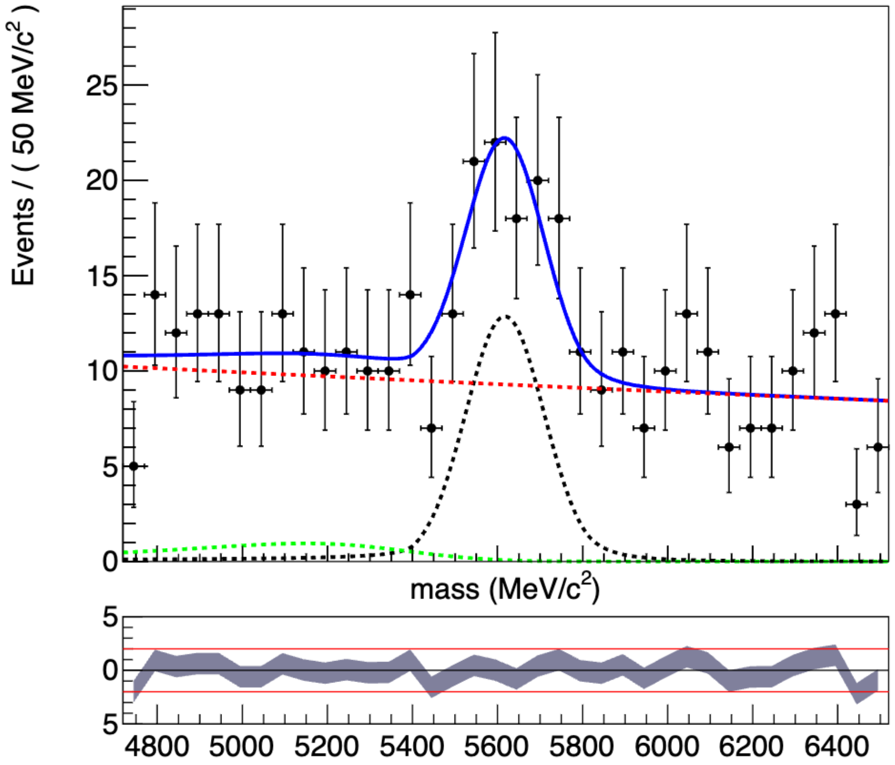
arXiv:1902.04870

$$W(\theta_\Lambda, \theta_p) \propto 1 - \alpha_\Lambda P_{\Lambda_b} \cos\theta_p \cos\theta_\Lambda - \alpha_\gamma(\alpha_\Lambda \cos\theta_p - P_{\Lambda_b} \cos\theta_\Lambda)$$



- Challenge: No Λ_b^0 vertex
- Signal excess with 5.6 σ significance.
  - 65 ± 13 candidates
  - First observation





- Uncertainty

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

Dominant systematic uncertainties on the measurement of $\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma)$

Source	Value (%)
$B^0 \to K^{*0}\gamma$ backgrounds	2.65
Λ_b^0 fit model	2.96
$f_{\Lambda_b^0}/f_{B^0}$	8.7
Input branching fractions	3.0
Limited MC statistics	1.7
Efficiency ratio	1.4
MC/Data	7.7
Total	12.8