Radiative b-hadron decays at LHCb

IFIC Scientific Day, L3: flavour and quark matter

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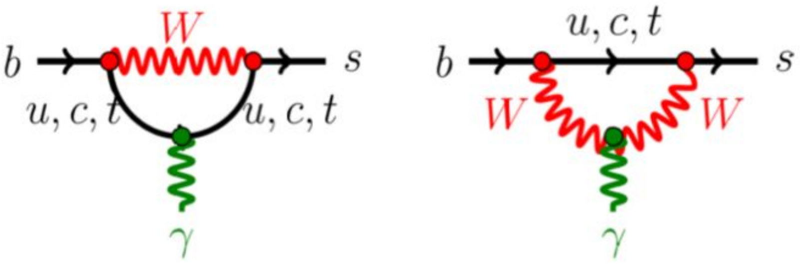
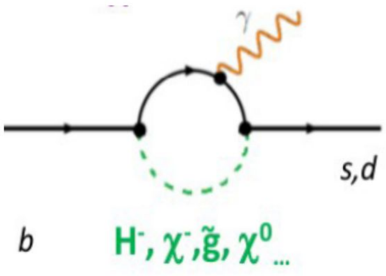
Outline

- **Introduction**
- **LHCb experiment**
- **$B_s \rightarrow \phi\gamma$ time dependent CPV analysis**
- **Radiative b-baryon decays**
  - Photon polarization in $\Lambda_b \rightarrow \Lambda\gamma$
  - Search for $\Xi_b^- \rightarrow \Xi^- \gamma$
- **NP constraints**
- **Summary**

Introduction

- The b → q γ radiative transitions (q=s,d) are Flavor-Changing Neutral Current (FCNC) processes that are only allowed at loop level in the SM.





- New physics affects the transition dynamics by modifying:

  ★ Phases
  ★ Amplitudes
  ★ Lorentz structure

Observables →

  ★ CPV
  ★ Branching ratios
  ★ Angular distributions

Introduction

- In Effective Field Theory (EFT) the effective hamiltonian of b → q γ radiative transitions is domained by EM dipole operators $\mathbf{O}_{7(L,R)}$

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

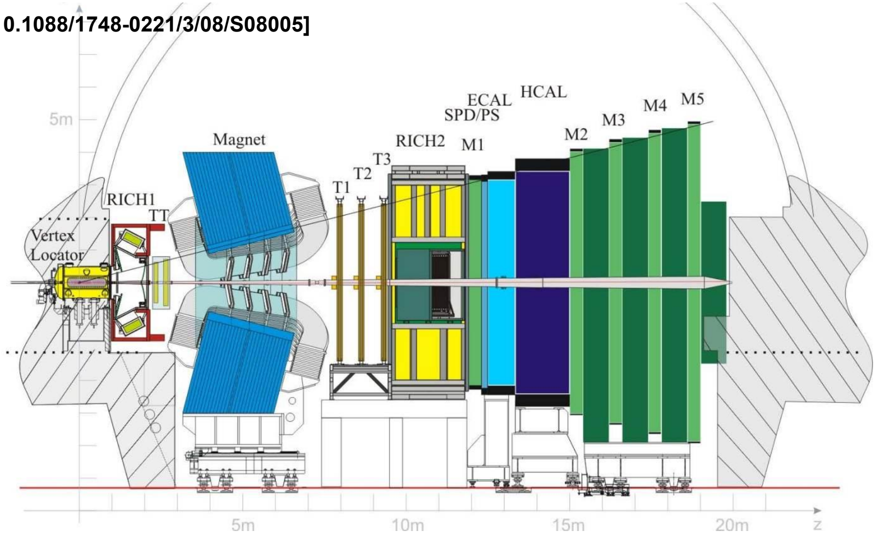
- The measurement of several observables provides different constraints in the C_7 – C_7' plane:

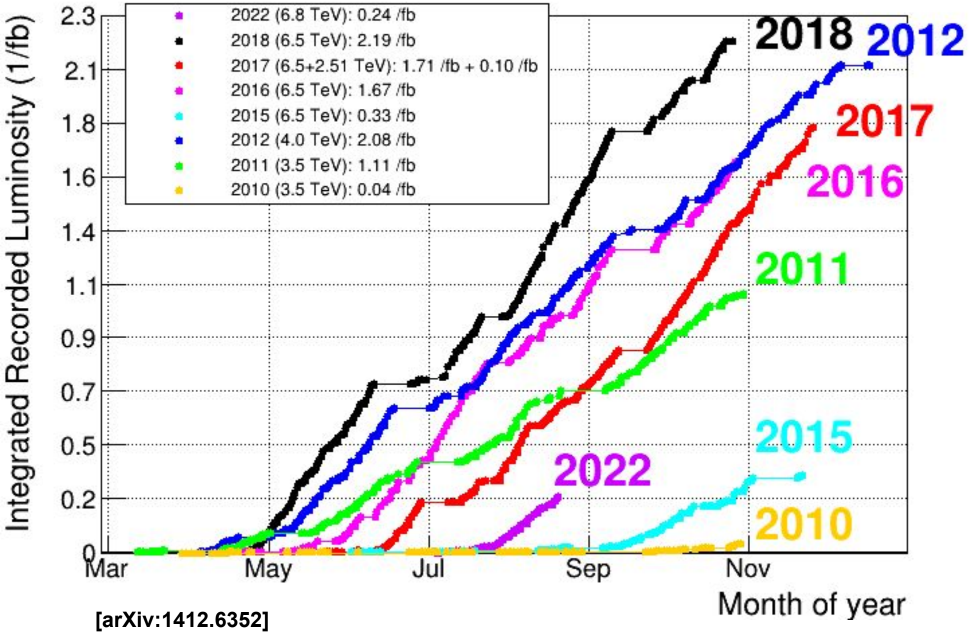
  - ❖ The branching ratio: $\propto (|C_7|^2 + |C_7'|^2)$
  - ❖ The photon polarization: $\propto \frac{1 - |C_7'|^2/|C_7|^2}{1 - |C_7'|^2/|C_7|^2}$
  - ❖ The CP Asymmetry: $\propto \mathrm{Im}\frac{C_7 C_7'}{|C_7'|^2 + |C_7|^2}$

The precise measurement of these observables gives constraints to NP models through Wilson coeficientes.

LHCb experiment

[10.1088/1748-0221/3/08/S08005]



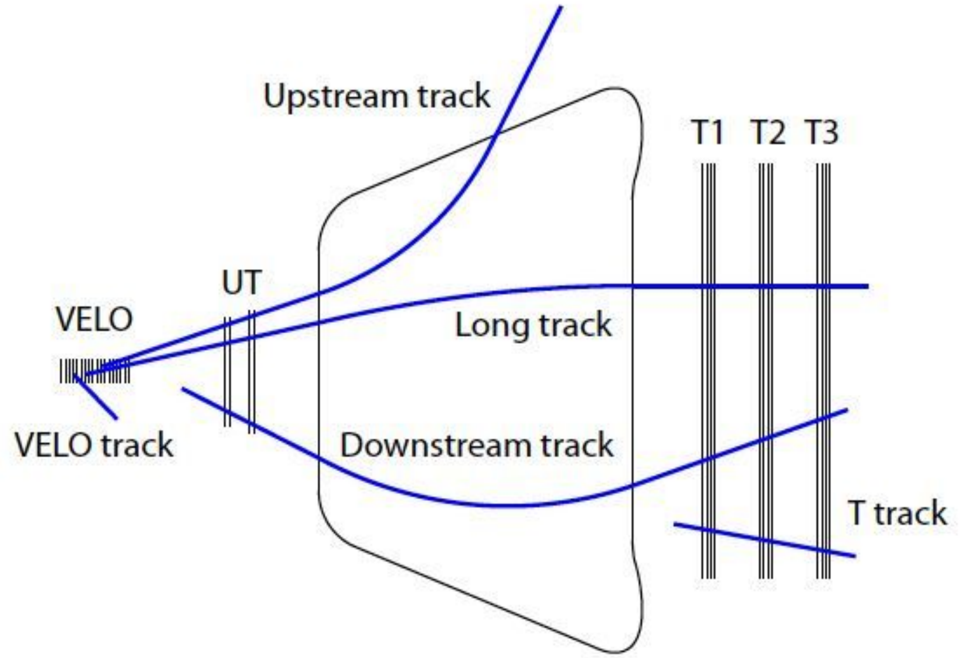


[arXiv:1412.6352]

- Forward spectrometer (2<η<5)
- 9 fb^{-1} data (Run1 + Run2)
- Excellent tracking ($\sigma(m_B)$~25 MeV for 2-body decays) and PID performance (μ_{ID}~97%)

LHCb experiment: Tracking system

- Reconstruct tracks of charged particles
- Most of LHCb analysis is based on Long tracks:
  - $\Delta p / p = 0.5 - 1.0\%$
  - $\Delta IP = (15 + 29/p_T[\mathrm{GeV}])\ \mu m$
- Long-lived particles need downstream tracks and T tracks
- **Only long tracks are available in HLT1 during Run1/2**



LHCb experiment: Photon reconstruction

- Two types of photons:
  - **Calorimetric photons**: *unconverted photons or conversion after magnet*, reconstructed from showers deposited in EM calorimeters.
  - **Di-electron photons**: *conversion before magnet*, reconstructed from tracking systems.

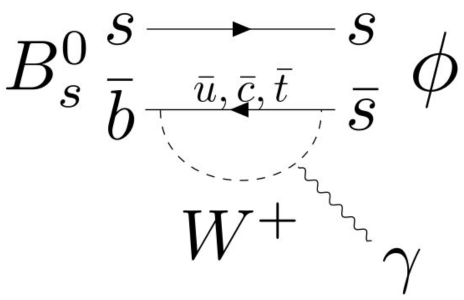
- Large calorimeter occupancy implicates large combinatorial backgrounds:
  - The trigger rely on high $\mathbf{p_T}$ photons: L0 threshold in 2011(2012) is $\mathbf{E_T(\gamma) > 2.5\ (3.0)\ GeV}$.
  - Typical trigger efficiency on radiative modes ~ **30-40 %** ($\varepsilon_{\mu\mu}$~80-90%).
  - The mass resolution is driven by calorimeter resolution: $\boldsymbol{\sigma_M[B \to X\gamma]}$**~90 MeV** ($\sigma_M[B \to hh]$~25 MeV).

$B_s \to \phi\gamma$ time dependent CPV analysis (Phys. Rev. Lett. 123 (2019) 081802)

- The $B_s \to \phi\gamma$ decay is a typical $b \to s\gamma$ transition case.
- The real photon (h=±1) implies the helicity flip on the quark lines:

$$b_R \to s_L\, \gamma_L \text{ or } b_L \to s_R\, \gamma_R$$

- The leading EM dipole operator in the effective Hamiltonian:



$$O_7 \propto m_b \bar{s}\sigma^{\mu\nu}F_{\mu\nu}(1+\gamma_5)b + m_s \bar{s}\sigma^{\mu\nu}F_{\mu\nu}(1-\gamma_5)b$$

$$\tan\psi = \left| A_R(b_L \to s_R\gamma_R) / A_L(b_R \to s_L\gamma_L) \right| \approx m_s / m_b$$

Right-Handed amplitude suppressed by m_s/m_b~2% → γ mostly Left-Handed

(Right-Handed component could be enhanced in NP models)

- The photon polarization can be extracted from the time-dependent analysis.

$B_s \to \phi\gamma$ time dependent CPV analysis (Phys. Rev. Lett. 123 (2019) 081802)

- The $B_s \to \phi\gamma$ decay rate is sensitive to the CPV and photon polarization:

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

Same for B_s and $\bar{B}_s$

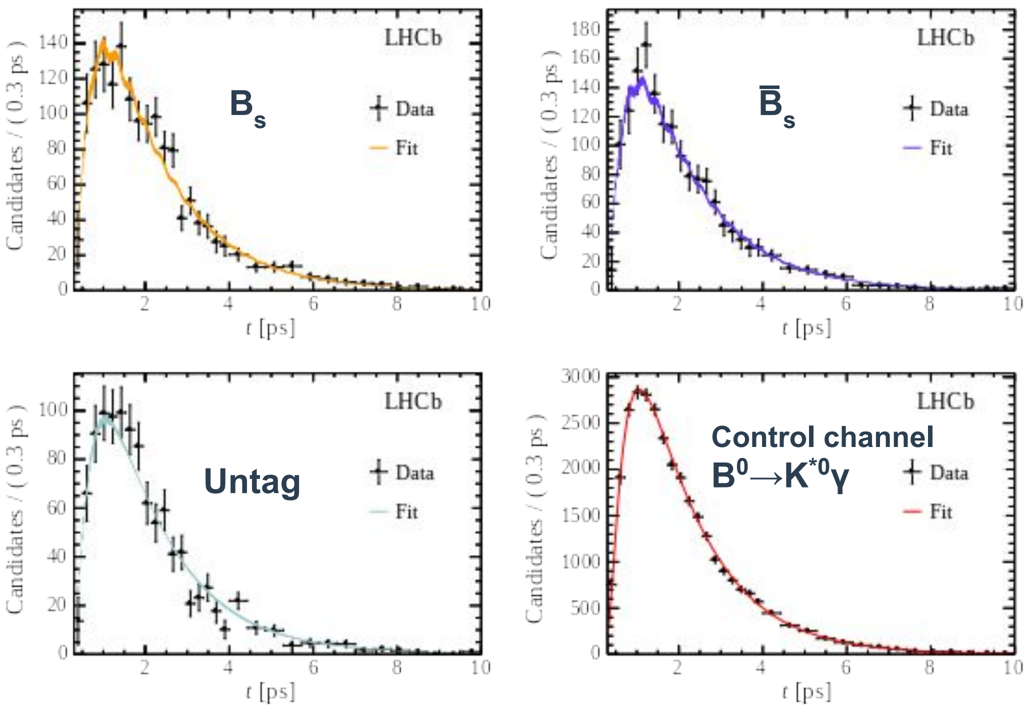
Required knowledge of the initial B_s flavour

  - **C** is sensitive to the direct CPV.
  - $\mathbf{A^{\Delta}}$ and **S** are sensitive to the photon polarization.
  - **S** is sensitive to the mixing-induced CPV, from SM prediction:

$$S_{O7} = -2\frac{m_s}{m_b}\sin(\phi_s - \phi_s) = 0 \quad \Longrightarrow \quad \text{Null-test of SM}$$

$B_s \rightarrow \phi\gamma$ time dependent CPV analysis (Phys. Rev. Lett. 123 (2019) 081802)

- **Current results**:

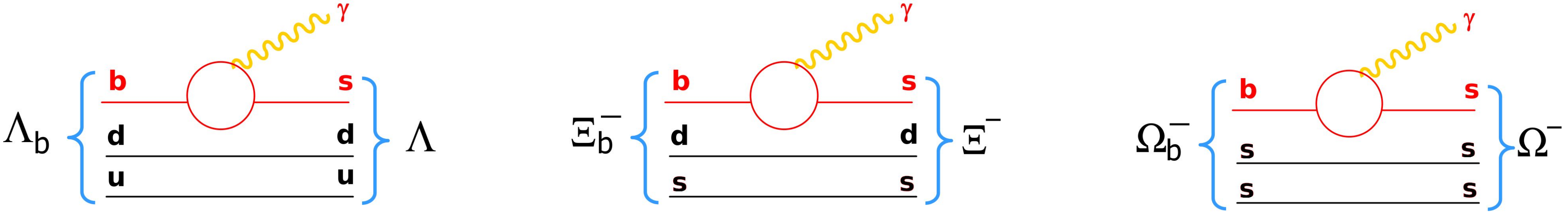


$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$

- Only using **Run1** Data (3 fb^{-1}).
- The results are compatible with the **SM** within 1.3, 0.3, 1.7 **standard deviations**.
- Uncertainties dominant by statistical uncertainty:
  - **On-going Run2** Analysis (6 fb^{-1})
  - **Run3** has started, the $B_s \rightarrow \phi\gamma$ mass peak is observed in 2023 data.

Radiative b-baryon decays

- **Decay products have long lifetime: cτ(Λ) ~ 8cm, cτ(Ξ) ~ 5cm → Long-lived particles**
- **Accessible at LHCb → branching ratio, photon polarization**
- **Possible decay channels:**
  - Λ_b radiative decay: $\mathbf{\Lambda_b \to (\Lambda \to p\,\pi^-)\,\gamma}$
  - $\Xi_b^-(\Omega_b^-)$ radiative decays: $\mathbf{\Xi_b^- \to (\Xi^- \to (\Lambda \to p\,\pi^-)\,\pi)\,\gamma}$ $\mathbf{\Omega_b^- \to (\Omega^- \to (\Lambda \to p\,\pi^-)\,K^-)\,\gamma}$

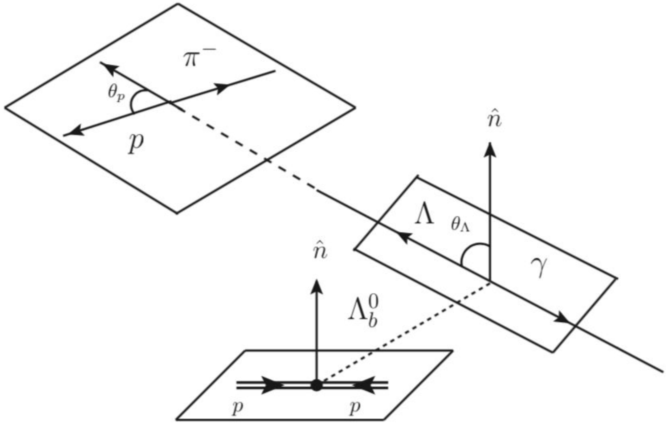


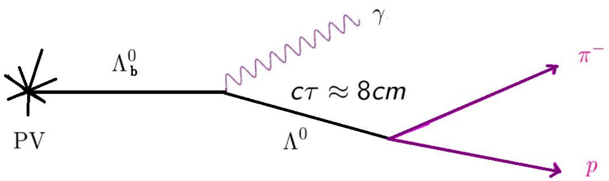
Photon polarization in $\Lambda_b \to \Lambda\gamma$ (PHYS. REV. D105 (2022) L051104)

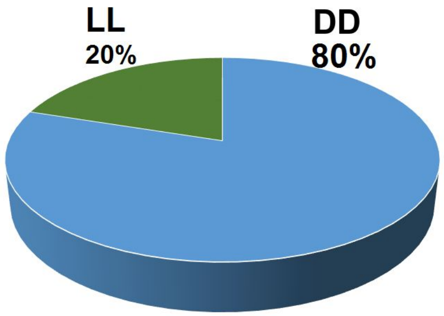
- **First angular analysis of radiative b-baryon decays (6 fb-1 of Run2 data):**
  - Follows first observation of (**65 ± 13**) events in **2016** data **[Phys. Rev. Lett. 123 (2019) 031801]**
  - **$B(\Lambda_b \to \Lambda\gamma) = (7.1 \pm 1.5) \times 10^{-6}$**
- **Extract γ-polarization (α_γ) from photon helicity angle θ_p:**

$$\frac{d\Gamma}{d(\cos\theta_p)} \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p, \qquad \alpha_\gamma = \frac{P(\gamma_L) - P(\gamma_R)}{P(\gamma_L) + P(\gamma_R)}$$

α_Λ: Λ weak decay parameter, BESIII input **[Nature Phys. 15 (2019) 631]**





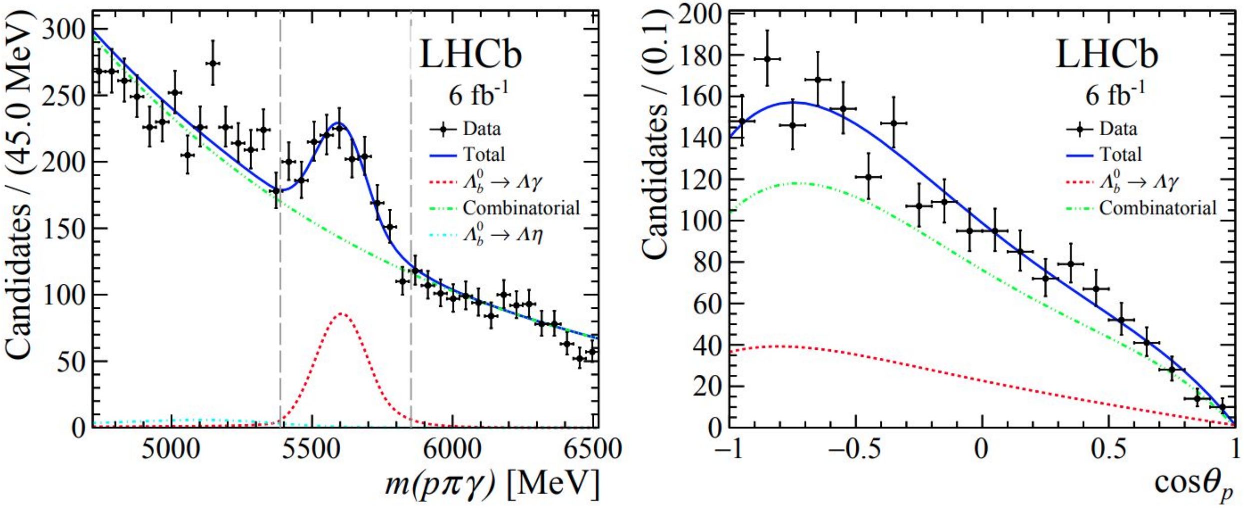


Photon polarization in $\Lambda_b \to \Lambda\gamma$ (PHYS. REV. D105 (2022) L051104)

- **Results:**

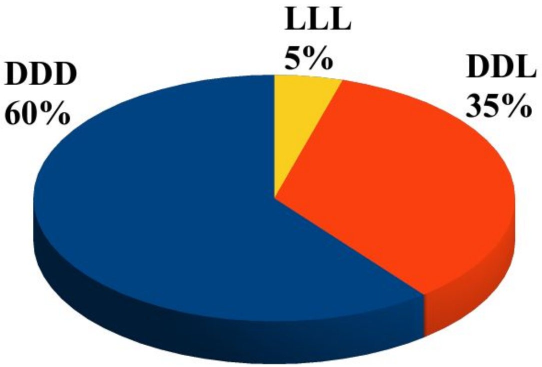
$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\ (\text{stat.})^{+0.04}_{-0.13}\ (\text{syst.})$$

Uncertainties dominated by statistics (440 ± 40 events) → Expected to be improved with Run3 data



Search for $\Xi_b^- \to \Xi^- \gamma$ (LHCb-PAPER-2021-017)

- Uses 5.4 fb^{-1} of Run2 LHCb data
- Consider only (LLL) decays contained in VELO (trigger limitation)
- Clean reconstructed Ξ^- and Λ
- Normalization and control with $\Xi_b^- \to \Xi^- J/\Psi$



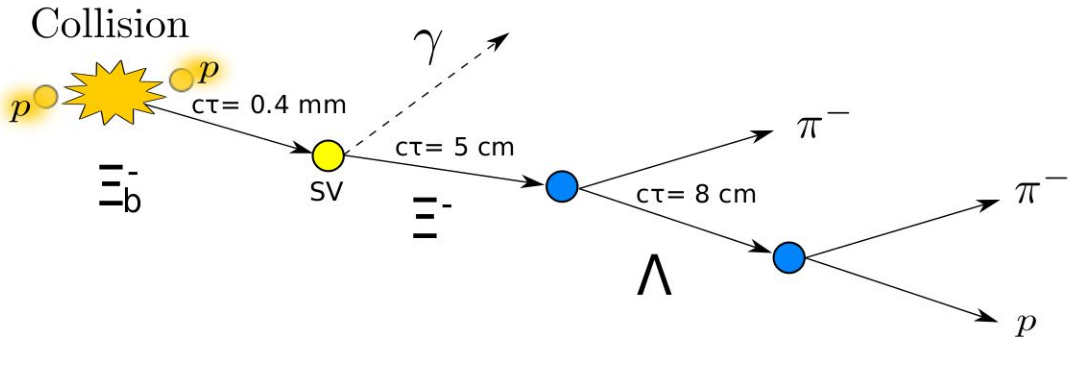
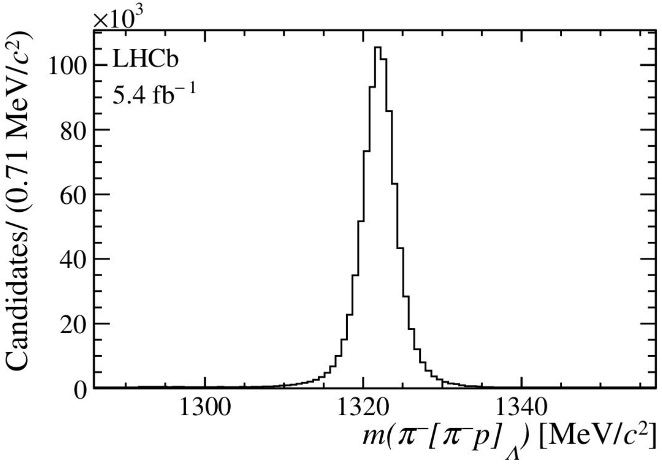


Figure 3: Topology of the $\Xi_b^- \to \Xi^- \gamma$ decay.



Search for $\Xi_b^- \to \Xi^- \gamma$ (LHCb-PAPER-2021-017)

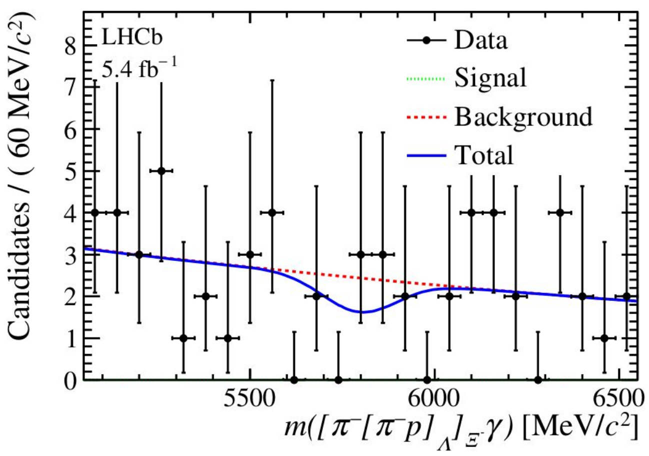
- **Results:**

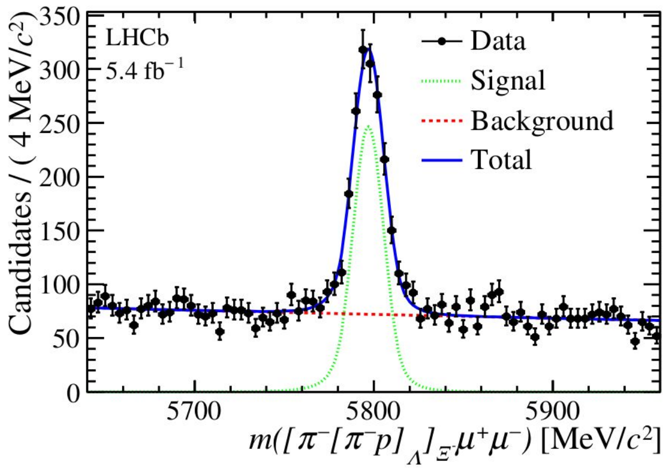
  N$(\Xi^- \gamma) = (-3.6 \pm 3.9)$, $N(\Xi^- J/\Psi) = (1407 \pm 52)$

  Br(SM prediction) = 1.23×10^{-5}

  $Br(\Xi_b^- \to \Xi^- \gamma) < 1.3(0.6) \times 10^{-4}$ at 95%(90%) CL

- **Expect large improvement of statistics in Run3: new triggers & high luminosity**

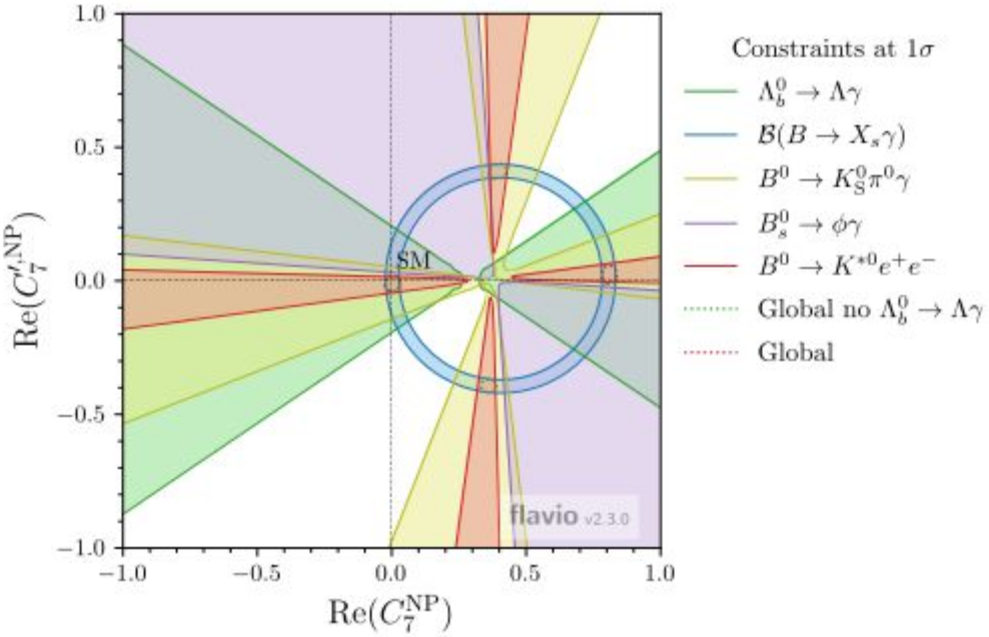


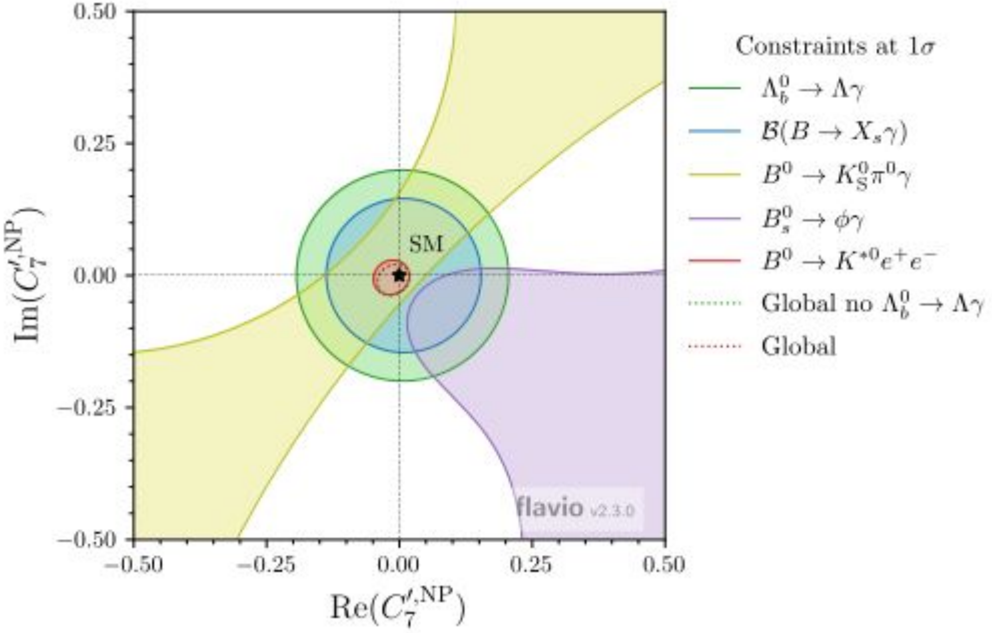


The dedicated trigger on these types of Long-lived particles may significantly improve this result.

The new HLT1 downstream trigger is available in Run3!

NP constraints





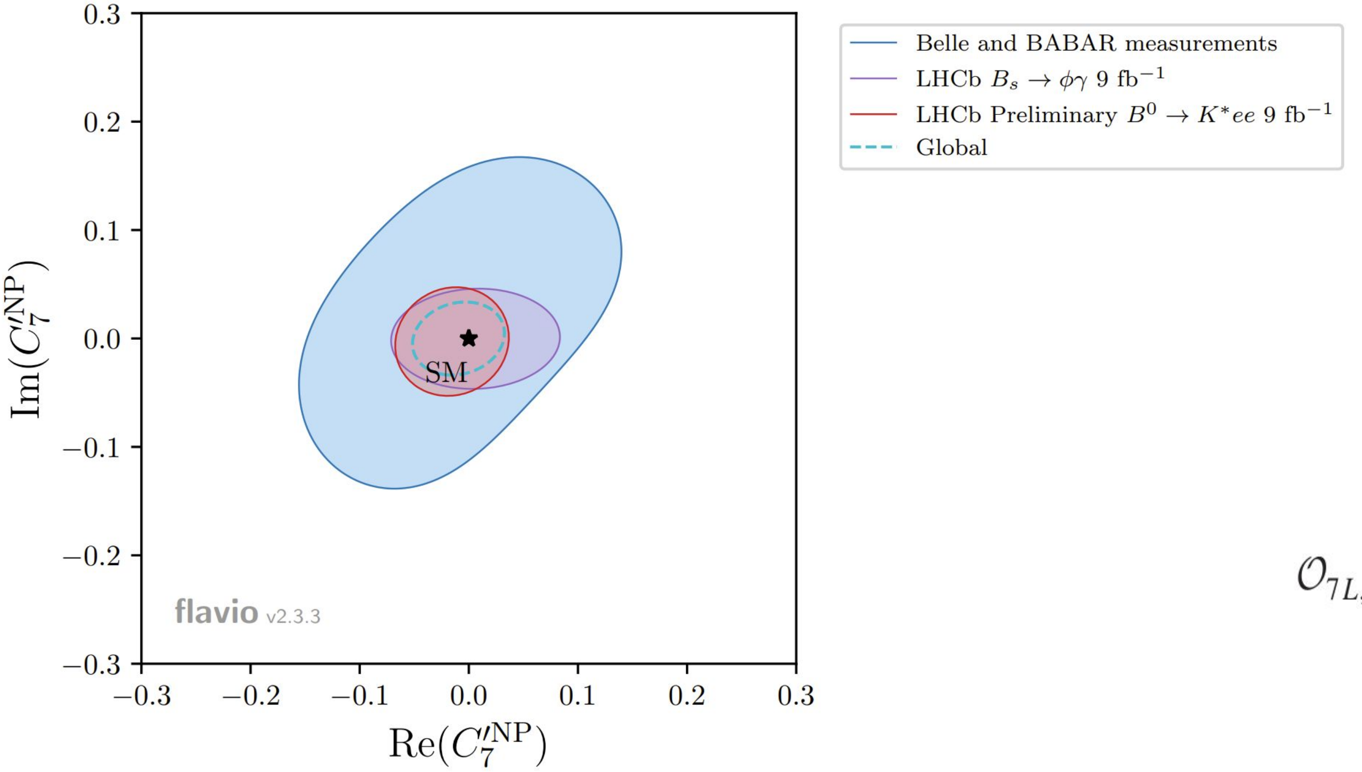
Summary

- **Radiative b-hadron decay** anomalies provide hints of **NP** through **branching ratios**, **CP asymmetries** and **photon polarisation**.
- **LHCb** provides a **unique laboratory** for precise measurements in radiative b-baryon decays:
  - World-largest radiative samples in several final states
  - Access to photon polarizations in many ways
- The **Run3** data-taking has started, the luminosity and trigger improvements will boost all statistically limited analysis: **[doi.org/10.3389/fdata.2022.1008737]**
  - Expected to accumulate ~23 fb^{-1} data at the end of Run3
  - The new **HLT1 trigger** on **downstream tracks** is now available in Run3.

    (Done by LHCb group in IFIC)

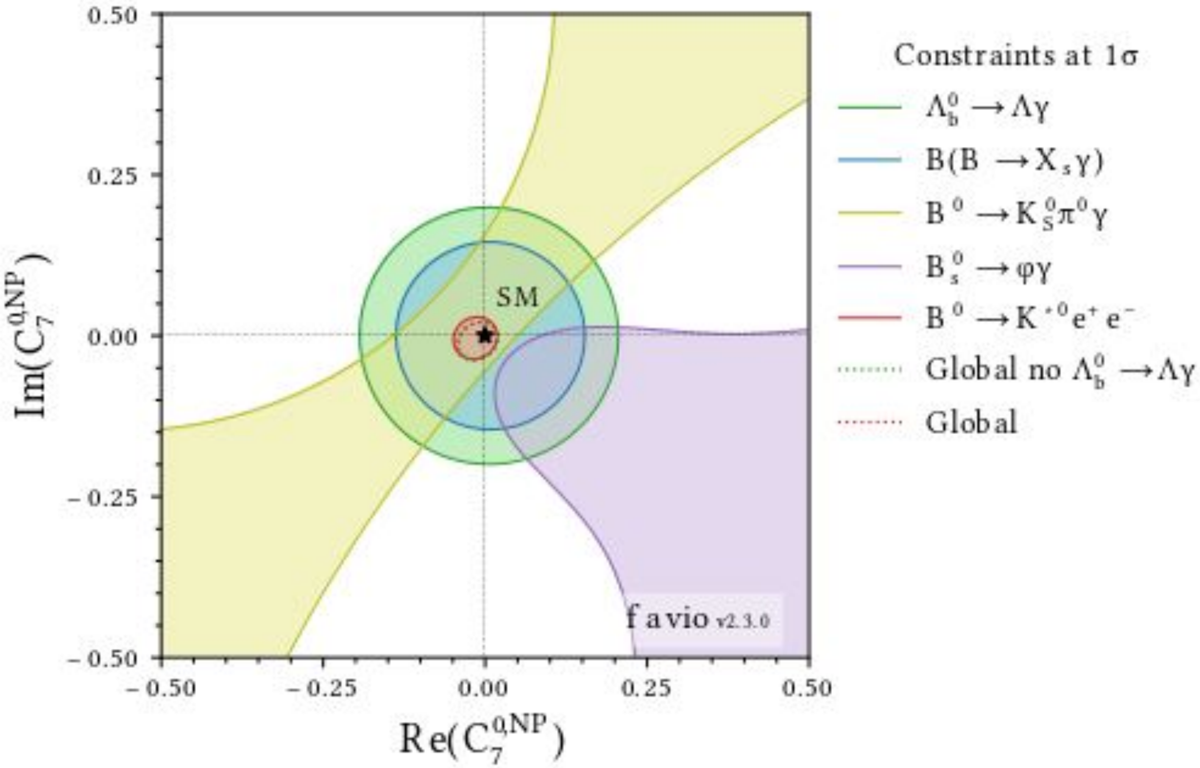

THANKS FOR LISTENING
ANY QUESTIONS?

Back up



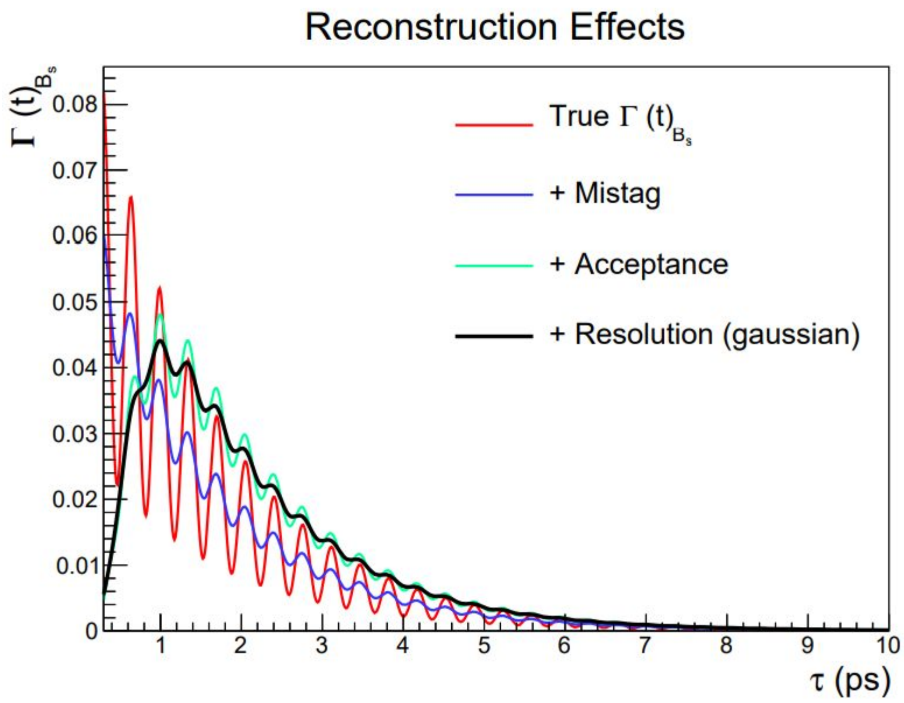
$$\mathcal{O}_{7L,R} = \frac{e}{16\pi^2} m_b \bar{s} \sigma_{\mu\nu} \frac{1 \pm \gamma_5}{2} b F^{\mu\nu}$$

Back up



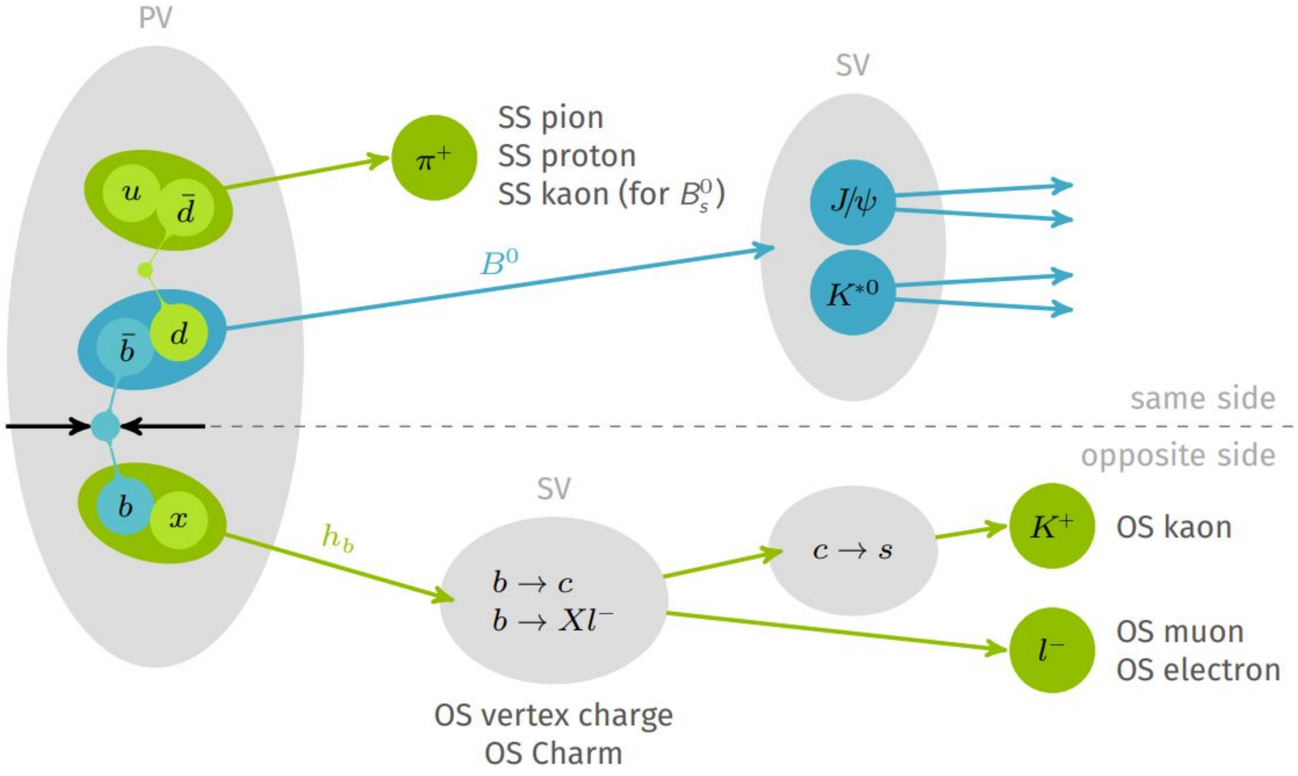
Constraints at 1σ
$\Lambda_b^0 \to \Lambda\gamma$
$B(B \to X_s\gamma)$
$B^0 \to K_S^0\pi^0\gamma$
$B_s^0 \to \varphi\gamma$
$B^0 \to K^{*0}e^+e^-$
Global no $\Lambda_b^0 \to \Lambda\gamma$
Global
SM
flavio v2.3.0
$\mathrm{Re}(C_7^{0,NP})$
$\mathrm{Im}(C_7^{0,NP})$

Back up



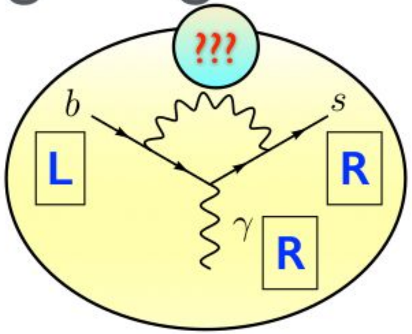
Reconstruction Effects
True Γ (t)Bs
+ Mistag
+ Acceptance
+ Resolution (gaussian)
Γ (t)Bs
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
5
6
7
8
9
10
τ (ps)

Back up



PV
SV
SS pion
SS proton
SS kaon (for B_s^0)
π^+
u
$\bar{d}$
B^0
d
$\bar{b}$
J/ψ
K^{*0}
same side
opposite side
b
x
h_b
SV
$b \to c$
$b \to Xl^-$
$c \to s$
K^+
OS kaon
l^-
OS muon
OS electron
OS vertex charge
OS Charm

Which NP models we are targeting?



- What types of new physics models?
  For example, models with right-handed neutrino, or custodial symmetry in general induces the right handed current.

Left-Right symmetric model (W_R)	SUSY GUT model δ_{RR} mass insertion
Blanke et al. JHEP1203	*Girrbach et al. JHEP1106*

- Which flavour/Dirac structure?
  The models that contain new particles which change the chirality inside of the b➔sγ loop can induce a large chiral enhancement!

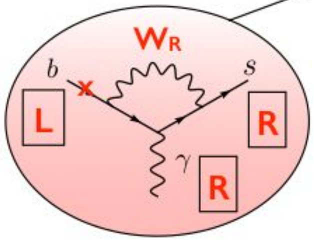
Left-Right symmetric model: mt/mb	SUSY with δ_{RL} mass insertions: m_{SUSY}/mb
Cho, Misiak, PRD49, '94 *Babu et al PLB333 '94*	*Gabbiani, et al. NPB477 '96* *Ball, EK, Khalil, PRD69 '04*

NP signal beyond the constraints from Bs oscillation parameters possible.

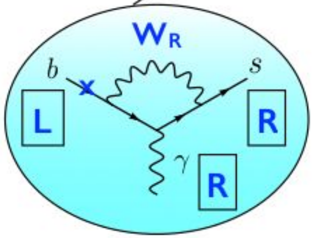
Chiral enhancement in LRSM

Right handed-photon contribution

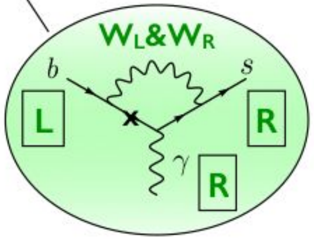
$$C'_{7\gamma}(\mu_R) = \frac{1}{2}\left[\frac{g_R^2}{g_L^2}\frac{V_{ts}^{R*}V_{tb}^{R}}{V_{ts}^{L*}V_{tb}^{L}}\left(\sin^2\zeta A_{\rm SM}(x_t) + \cos^2\zeta \frac{M_1^2}{M_2^2}A_{\rm SM}(\tilde{x}_t)\right)\right.$$
$$+ \frac{m_t}{m_b}\frac{g_R}{g_L}\frac{V_{ts}^{R*}}{V_{ts}^{L*}}\sin\zeta\cos\zeta e^{-iw}\left(A_{\rm LR}(x_t) - \frac{M_1^2}{M_2^2}A_{\rm LR}(\tilde{x}_t)\right) + \ldots$$



W_R contribution from W_1;
Proportional to mb but
suppressed by $1/M_2^2$



W_R contribution from W_2;
Proportional to mb



W_L & W_R mixing
contribution;
proportional to mt !

Chiral enhancement term