

# Prospects on the measurement of the $B_s^0 \rightarrow \phi\gamma$ photon polarization at LHCb

Pablo Ruiz Valls (IFIC, Valencia)



# Outline

- Introduction
- A bit of theory
  - The  $b \rightarrow s\gamma$  radiative penguin and the polarization fraction
  - The case of the  $B_s^0$  meson
  - Sensitivity to NP
- Probing the photon polarization in LHCb
- Conclusions

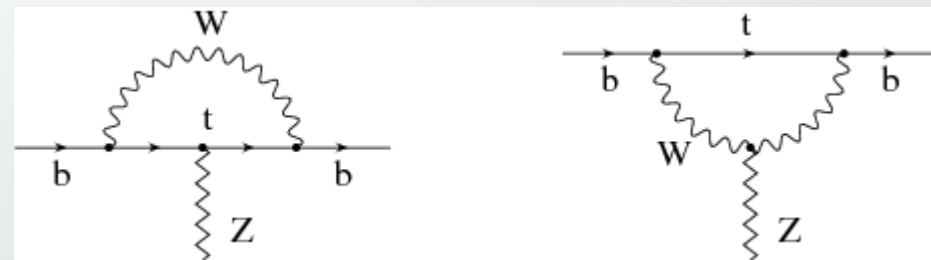
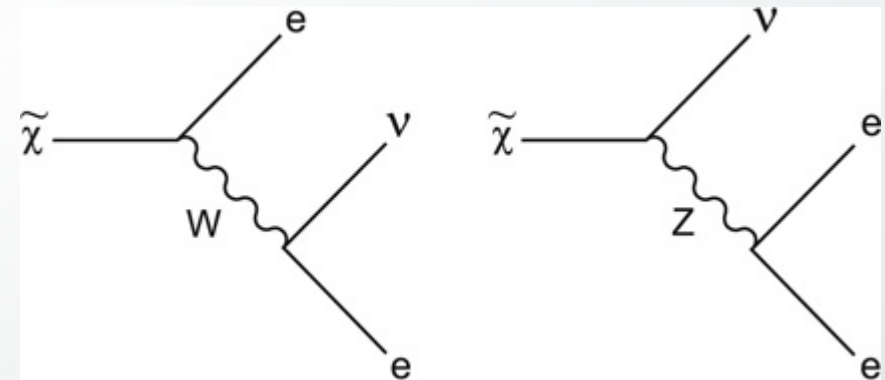
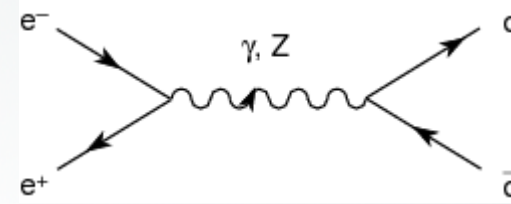
# Introduction

- The field of flavor physics is consistently reaping results, with great agreement between experiment and theory.
  - No clear signal of Beyond Standard Model physics (...?)
  - But SM is not the end of the story
    - Known unknowns: Mass hierarchy, neutrino mixing, dark matter, etc...
- The quest for new physics



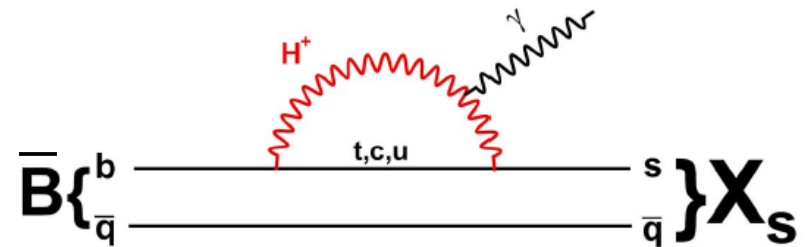
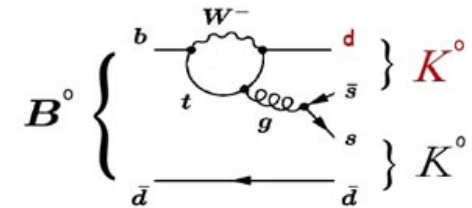
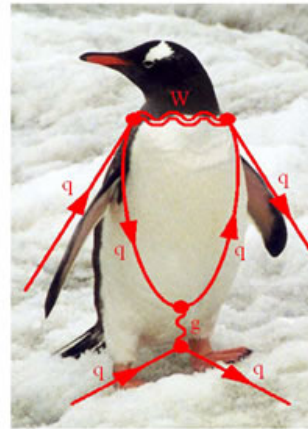
# Introduction

- Tree Level processes
  - Production of particles (eg. Z boson)
  - Leading order decays (eg. neutralino  $\rightarrow 2e\nu$ )
- Loops
  - Sometimes appear as N[N...]LO corrections to amplitudes



# Introduction

- But some processes are forbidden at tree level, such as Flavor changing neutral currents (FCNC), and the leading order must have loops
- Penguin diagrams
  - Great probes for NP
  - More rare than tree level decays
    - Small branching fractions
      - $< O(10^{-5})$
    - Experimentally challenging

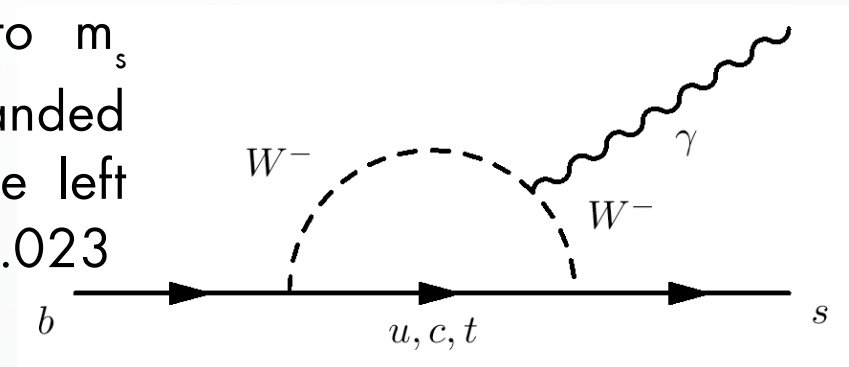


# The $b \rightarrow s\gamma$ penguin

- The  $b \rightarrow s\gamma$  transition, when described in the SM by the effective weak hamiltonian in terms of Wilson coefficients  $C_i$  and local operators  $O_i$ , the dominant contribution comes from the magnetic operator

$$O_{7\gamma} = \frac{e}{16\pi^2} [m_b (\bar{s}_{L\alpha} \sigma^{\mu\nu} b_{R\alpha}) + m_s (\bar{s}_{R\alpha} \sigma^{\mu\nu} b_{L\alpha})] F_{\mu\nu}$$

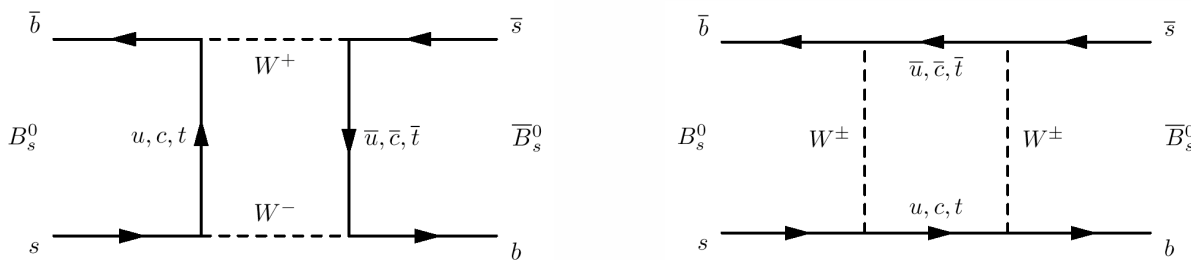
- In which the term proportional to  $m_s$  describes the emission of right handed photons, greatly suppressed wrt the left handed component, since  $m_s/m_b = 0.023$



- How to access the polarization fraction experimentally?

# B meson decays

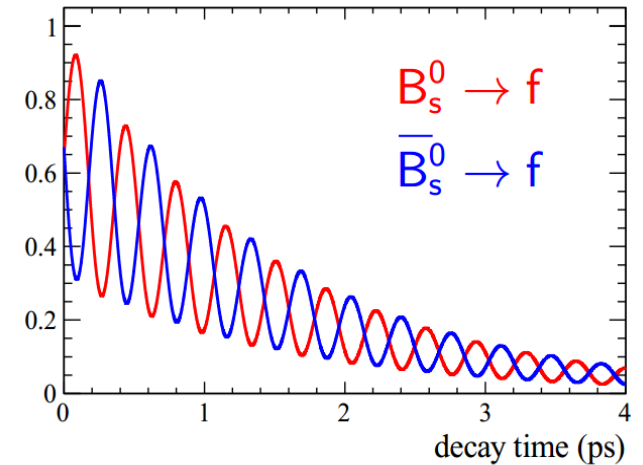
- Neutral mesons undergo flavor oscillations (mixing) through box diagrams, for the  $B_s^0$  meson:



- For  $\bar{b}(b)$  mesons (at  $t=0$ ) decaying to a CP eigenstate with a photon, the time dependent decay width is in general:

$$\Gamma(B_q(\bar{B}_q) \rightarrow f^{CP} \gamma)[t] \propto e^{-\Gamma_q t} \left( \cosh \frac{\Delta\Gamma_q t}{2} - A^\Delta \sinh \frac{\Delta\Gamma_q t}{2} \pm C \cos \Delta m_q t \mp S \sin \Delta m_q t \right)$$

- With  $\phi$  the mixing angle and  $\tan \psi$  the 'wrongly' polarized fraction
- $\Delta\Gamma_q$  ( $\Delta m_q$ ) is the decay width (mass) difference of mass eigenstates



$$A^\Delta = \sin(2\psi) \cos \phi \quad \tan \psi = \frac{\bar{B} \rightarrow f^{CP} \gamma_R}{\bar{B} \rightarrow f^{CP} \gamma_L}$$

# The $B_s^0$ meson

- One can measure the time dependent CP asymmetry

$$A_{CP}(B_s^0 \rightarrow \phi \gamma)[t] = \frac{N_{\bar{B}_s^0 \rightarrow \phi \gamma}(t) - N_{B_s^0 \rightarrow \phi \gamma}(t)}{N_{\bar{B}_s^0 \rightarrow \phi \gamma}(t) + N_{B_s^0 \rightarrow \phi \gamma}(t)} = \frac{S \sin(\Delta m_q t) - C \cos(\Delta m_q t)}{\cosh\left(\frac{\Delta \Gamma_s}{2} t\right) - A^\Delta \sinh\left(\frac{\Delta \Gamma_s}{2} t\right)}$$

$B_s^0$  meson 2012 PDG values

$B_s^0 = \bar{b} s, \bar{B}_s^0 = \bar{s} b$

$m_{B_s^0} = 5366.77 \pm 0.24 \text{ MeV}$

$\tau = (1.497 \pm 0.015) \times 10^{-12} \text{ s}$

$\Delta \Gamma_{B_s^0} = \Gamma_{B_{sL}^0} - \Gamma_{B_{sH}^0} = (0.100 \pm 0.013) \times 10^{-12} \text{ s}^{-1}$

$\Delta m_{B_s^0} = m_{B_{sH}^0} - m_{B_{sL}^0} = (0.100 \pm 0.013) \times 10^{-10} \text{ MeV}$

- The SM prediction for  $A^\Delta$  is  $0.047 \pm 0.025$  [Muheim et al., Phys.Lett.B664:174-179,2008]
- For  $B^0$  mesons the sinh vanishes, since  $\Delta \Gamma_d$  is  $\ll 1$
- The advantage of the  $B_s^0$  is that it has a sizable  $\Delta \Gamma$ 
  - Sensitivity to the  $A^\Delta$  parameter



# The $B_s^0$ meson

- If we avoid tagging altogether, the time dependent decay rate

$$\Gamma(B_q(\bar{B}_q) \rightarrow f^{CP} \gamma)[t] \propto e^{-\Gamma_q t} \left( \cosh \frac{\Delta\Gamma_q t}{2} - A^\Delta \sinh \frac{\Delta\Gamma_q t}{2} \pm C \cos \Delta m_q t \mp S \sin \Delta m_q t \right)$$

can be written as the sum of both flavors, and only the hyperbolic components survive, assuming both flavors share the same partial decay widths:

$$\Gamma(B_q)_{\text{Untagged}}[t] \propto e^{-\Gamma_q t} \left( \cosh \frac{\Delta\Gamma_q t}{2} - A^\Delta \sinh \frac{\Delta\Gamma_q t}{2} \right)$$

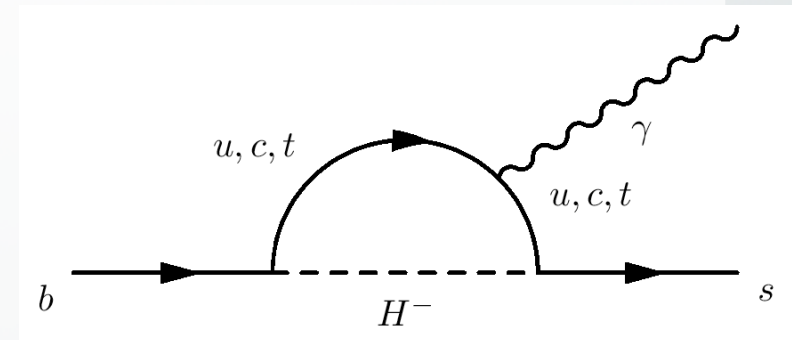
And for small  $A^\Delta$  we can approximate

$$\Gamma(B_q)_{\text{Untagged}}[t] \propto e^{-\Gamma_q t} \left[ 1 - \frac{A^\Delta \Delta\Gamma_q t}{2} + \frac{1}{2} \left( \frac{A^\Delta \Delta\Gamma_q t}{2} \right)^2 + \dots \right] \approx |A|^2 e^{-\Gamma_q^{\text{eff}} t}$$

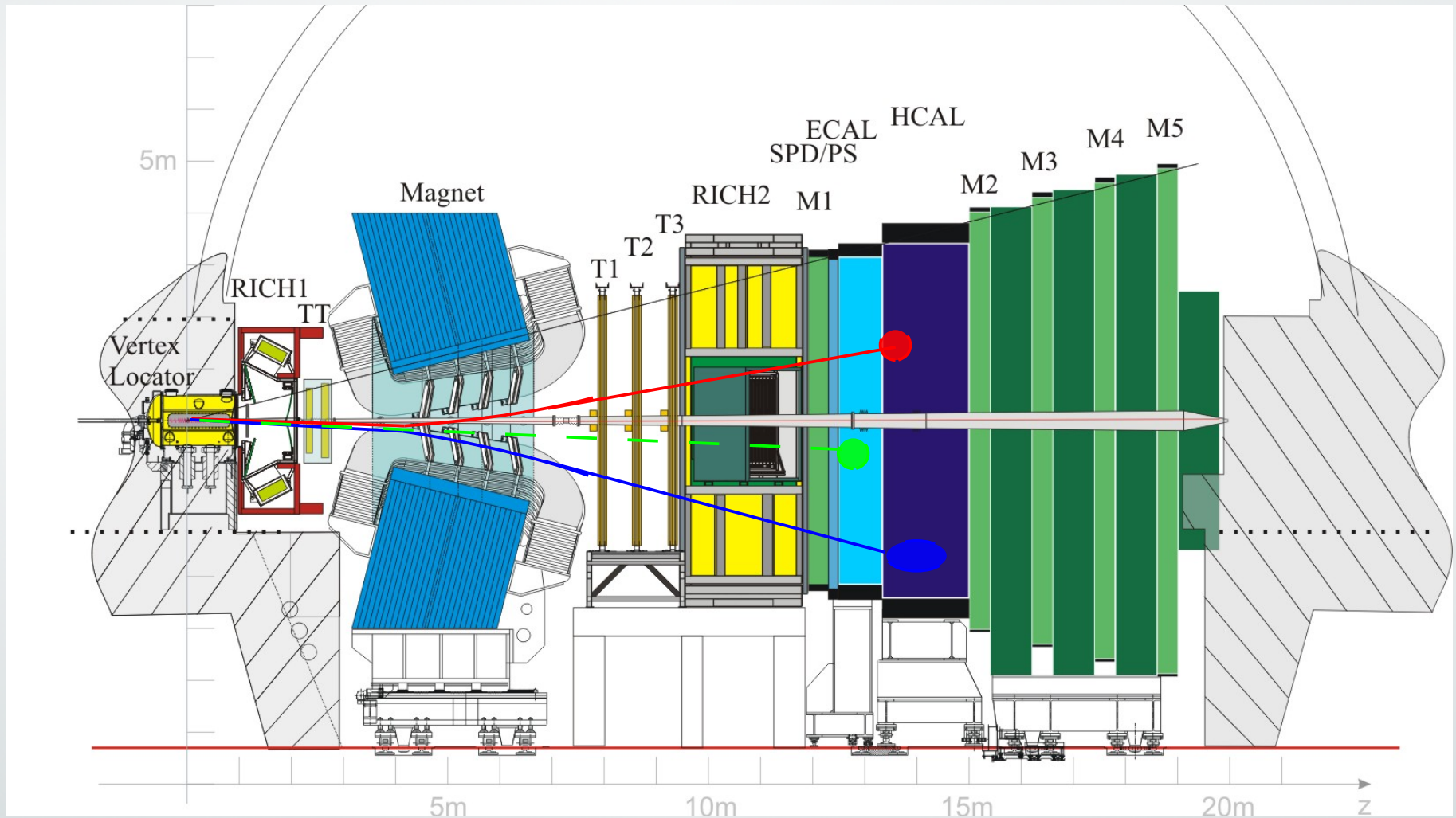
$$\text{where } \Gamma_q^{\text{eff}} = \Gamma_q + \frac{A^\Delta \Delta\Gamma_q}{2}$$

# Sensitivity to NP

- Other models can be probed through this observable
  - In the Left Right Symmetric Model (LRSM),  $A^\Delta$  can be as high as 0.7 [Atwood et al. arXiv:hep-ph/9704272v1]
  - Other models that involve new particles participating in the loop could modify the properties of this decay
    - Two Higgs doublet models (2HDM)
    - SUSY
- Updated theoretical predictions would be desirable



# The LHCb Detector



# Radiative decays at LHCb

- LHCb has published measurements on radiative decays such as

- The ratio of Branching fractions of  $B^0 \rightarrow K^{*0} \gamma$  and  $B_s^0 \rightarrow \phi \gamma$

$$\frac{\mathcal{B}(B^0 \rightarrow K^{*0} \gamma)}{\mathcal{B}(B_s^0 \rightarrow \phi \gamma)} = 1.23 \pm 0.06 (\text{stat.}) \pm 0.04 (\text{syst.}) \pm 0.10 (f_s/f_d)$$

- The direct CP violation in  $B^0 \rightarrow K^{*0} \gamma$

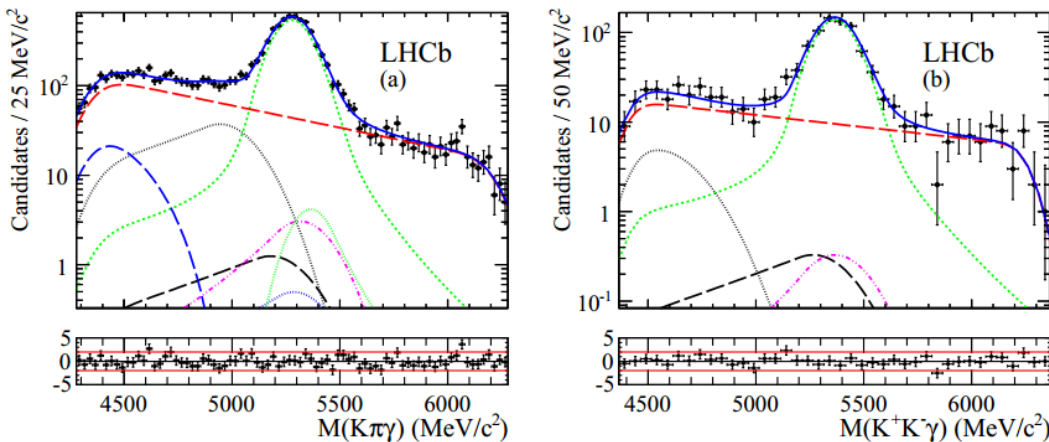
$$\mathcal{A}_{CP}(B^0 \rightarrow K^{*0} \gamma) = (0.8 \pm 1.7 (\text{stat.}) \pm 0.9 (\text{syst.}))\%$$

Both Nuclear Physics, Section B 867 (2013), pp. 1-18

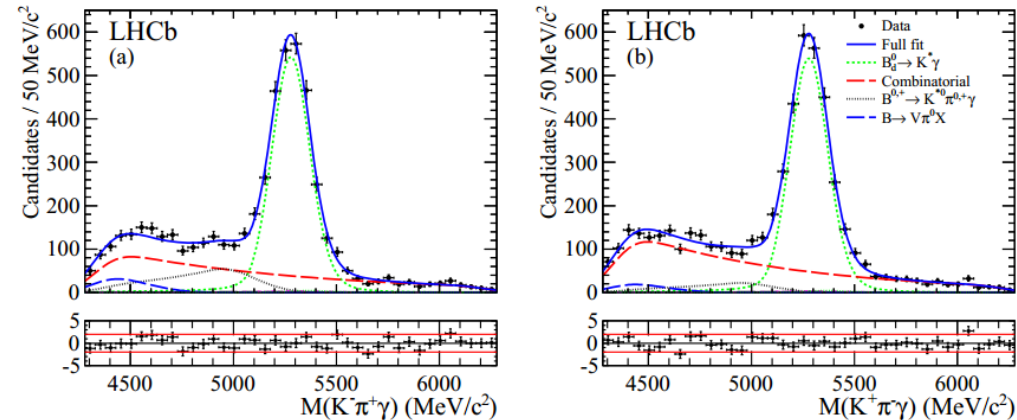
- Most precise measurements to date



**More on these results during the LHC session in A. Oyanguren's talk**



Invariant-mass distributions of the (a)  $B^0 \rightarrow K^{*0} \gamma$  and (b)  $B_s^0 \rightarrow \phi \gamma$  candidates.



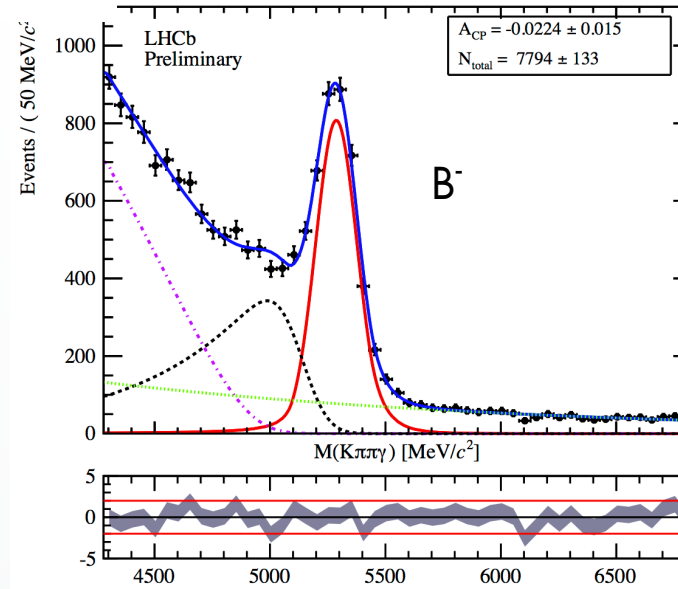
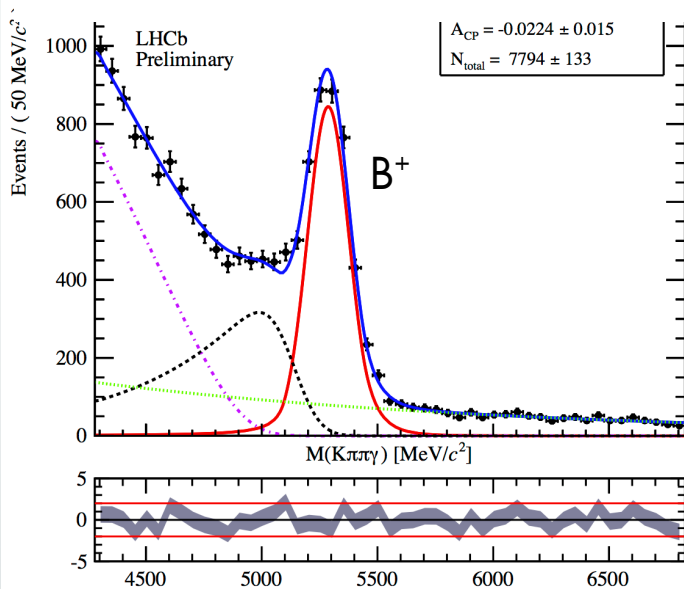
Invariant-mass distributions of the (a)  $\bar{B}^0 \rightarrow \bar{K}^{*0} \gamma$  and (b)  $B^0 \rightarrow K^{*0} \gamma$  decay candidates.

# Radiative decays at LHCb

- CP and up-down asymmetries in  $B^+ \rightarrow (K\pi\pi)^+\gamma$  decay<sup>[LHCb-CONF-2013-009]</sup>

$$A_{CP} = -0.007 \pm 0.015 \text{ (stat)}_{-0.011}^{+0.012} \text{ (syst)}$$

$$A_{ud} = -0.085 \pm 0.019 \text{ (stat)} \pm 0.004 \text{ (syst)}$$



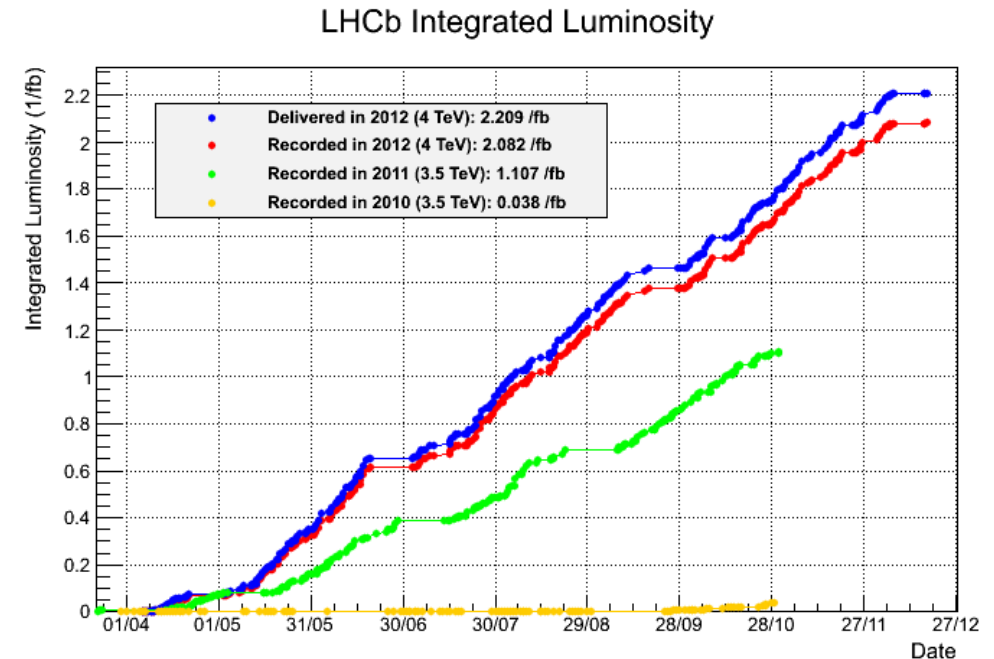
**More on these results during the LHC session in A. Oyanguren's talk**

- The branching fraction of  $B^0 \rightarrow K^{*0} e^+ e^-$  at low dilepton mass<sup>[arXiv:1304.3035, submitted to JHEP]</sup>

$$\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)_{30-1000 \text{ MeV}/c^2} = (3.1_{-0.8}^{+0.9} \text{ }_{-0.3}^{+0.2} \pm 0.2) \times 10^{-7}$$

# $B_s^0 \rightarrow \phi \gamma$ in LHCb

- $3 \text{ fb}^{-1}$  collected in 2011 (7 TeV)-2012 (8 TeV)
- Long shutdown (LS1) 2013-2014
- Accumulate up to  $7 \text{ fb}^{-1}$  2015-2017 at 14 TeV
- **Upgrade** in LS2 2018
- $5 \text{ fb}^{-1}$  per year to  $50 \text{ fb}^{-1}$  in total
  - BaBar/Belle collected  $1.2 \text{ ab}^{-1}$  at  $\Upsilon(4S)$ 
    - Mostly  $B\bar{B}$  ( $1 \text{ nb}$ )
  - Belle II  $50 \text{ ab}^{-1}$  expected ( $\sim 2020$ )
- LHCb  $pp \rightarrow b\bar{b}$  pair production cross section
  - $284 \mu\text{b}$  at 7 TeV<sup>[Phys.Lett.B694:209-216,2010]</sup>
  - $527.3 \mu\text{b}$  at 14 TeV<sup>[sim]</sup>
- Hadronization fraction to  $B_s^0$ ,  $f_s = 9\%$ <sup>[Phys. Rev. D 85, 032008 (2012)]</sup>

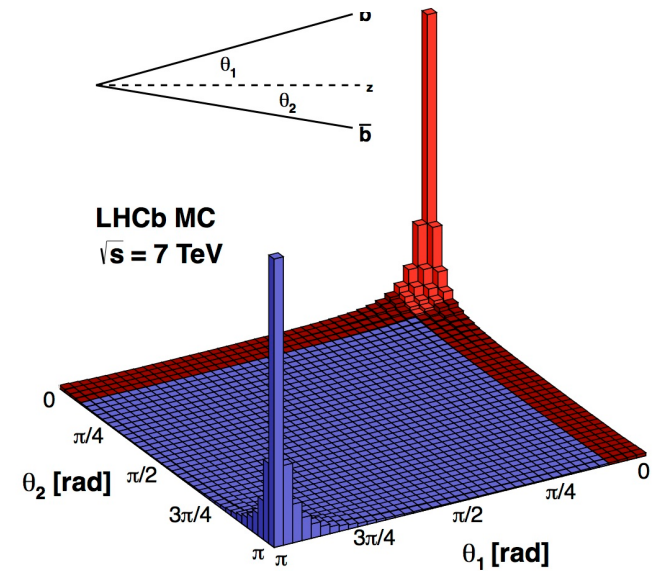


# $B_s^0 \rightarrow \phi \gamma$ in LHCb

- We can then estimate a  $B_s^0$  production cross section
  - 51.2  $\mu\text{b}$  at 7 TeV, 95  $\mu\text{b}$  at 14 TeV
- Measurement of  $B_s^0$  production cross section at 7 TeV<sup>[JHEP08(2013)117]</sup> (including detector acceptance )

$$\sigma(pp \rightarrow B_s^0 + X) = 10.5 \pm 0.2 (\text{stat.}) \pm 0.8 (\text{syst.}) \pm 1.0 (\text{norm.}) \mu\text{b},$$

- $BR(B_s^0 \rightarrow \phi \gamma) = (5.7 \pm 0.3) \cdot 10^{-5}$
- $BR(\phi \rightarrow K^+ K^-) = 0.489 \pm 0.005$
- $B_s^0 \rightarrow \phi (\rightarrow K^+ K^-) \gamma$  produced per  $\text{fb}^{-1}$ 
  - 584k at 7 TeV
  - 1086k at 14 TeV
- 52 M produced in total with 50  $\text{fb}^{-1}$

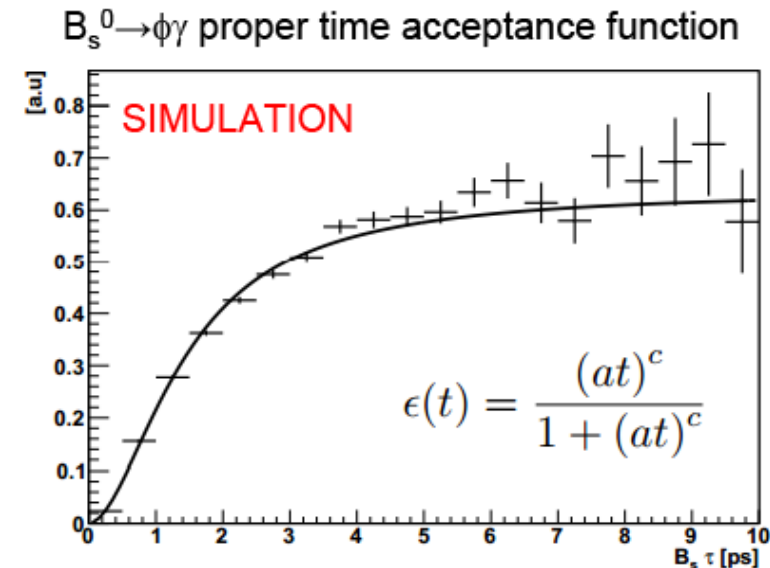


# $B_s^0 \rightarrow \phi \gamma$ in LHCb

- Acceptance and experimental efficiency (Trigger, Reconstruction, Selection...) further reduces the available signal yield
  - Current selection yield is  $\sim 2\text{k}$  signal events with  $3\text{fb}^{-1}$
  - Selection currently being optimized to maximize the efficiency
    - Multivariate methods studied considerably improve the signal yield wrt a cut based strategy
- Uncertainties are at present statistically dominated

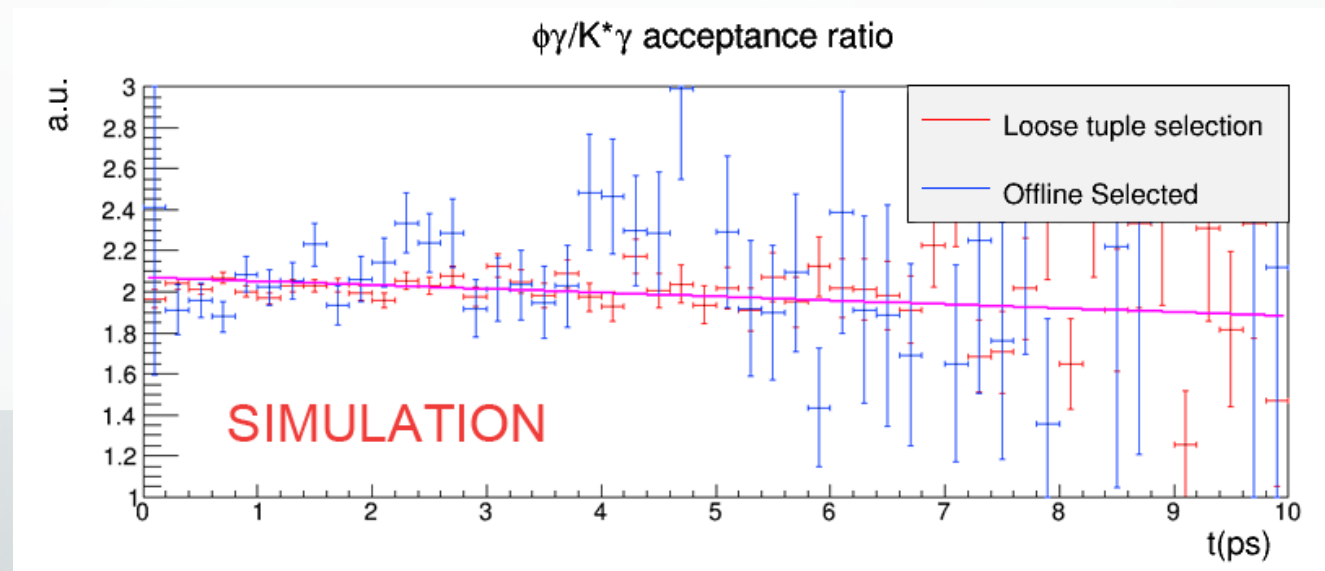
# $B_s^0 \rightarrow \phi \gamma$ photon polarization

- We aim to measure the photon polarization fraction
- Currently the fit framework is under development, several options being explored
  - Untagged ML  $B_s^0$  lifetime fit
    - The proper time acceptance function must be well determined
    - Extract the proper time acceptance function from a fit to the control channel ( $B^0 \rightarrow K^{*0} \gamma$ )
      - Higher yield



# $B_s^0 \rightarrow \phi \gamma$ photon polarization

- Fit framework under development, several options being explored
  - Binned lifetime ratio ( $B_s^0 \rightarrow \phi \gamma / B^0 \rightarrow K^{*0} \gamma$ )
    - Similar resolution functions
    - Acceptance ratio is flat and well known after carefully designing the selection
    - Statistical sensitivity to  $A^\Delta$  under study
      - estimated around 0.4 for 2k  $B_s^0$  events



- Fit the relative lifetime  $\Gamma_{\text{eff}}(B_s^0 \rightarrow \Phi\gamma) - \Gamma(B_d^0 \rightarrow K^*\gamma)$  without flavor tagging

$$\frac{d\Gamma_{B_s^0}/dt}{d\Gamma_{B_d^0}/dt} \approx \frac{N_{B_s^0}}{N_{B_d^0}} \cdot \frac{\hat{\epsilon}_{B_s^0}(t)}{\hat{\epsilon}_{B_d^0}(t)} \cdot \frac{\Gamma_{B_s^0} + A^\Delta \cdot \Delta\Gamma_{B_s^0}/2}{\Gamma_{B_d^0}} \cdot \frac{e^{\left(\Gamma_{B_s^0} + \frac{A^\Delta \cdot \Delta\Gamma_{B_s^0}}{2}\right) \cdot t} \otimes R_{B_s^0}(t, t')}{e^{\Gamma_{B_d^0} \cdot t} \otimes R_{B_d^0}(t, t')}$$

$\Delta\Gamma_{B_d^0} \ll$

$$N_{B_i} = L \sigma_{pp \rightarrow b\bar{b}} 2 f_i \mathfrak{B}(B_i \rightarrow V \gamma) \mathfrak{B}(V \rightarrow Kh) \epsilon_{B_i}$$

obtained from fit to  $B_i$  mass peak

Projecting to  $3\text{fb}^{-1}$  (from Nuclear Physics, Section B 867 (2013), pp. 1-18)

$$\frac{N_{B_s^0}}{N_{B_d^0}} = \frac{1}{7.63 \pm 0.38 \pm 0.17} \text{ for } 1 \text{ fb}^{-1} \rightarrow (3\%)$$

$$\frac{\hat{\epsilon}_{B_s^0}}{\hat{\epsilon}_{B_d^0}} = \text{flat acceptance ratio}$$

$$A^\Delta = 0.047 (SM)$$

From PDG

$$\Delta\Gamma_{B_s^0} = 0.100 \pm 0.013 \text{ ps}^{-1} (13\%)$$

$$\Gamma_{B_s^0} = 0.668 \pm 0.007 \text{ ps}^{-1} (1.05\%)$$

$$\Gamma_{B_d^0} = 0.658 \pm 0.003 \text{ ps}^{-1} (0.46\%)$$

# Conclusions

- Flavor physics has been a great testing ground for the SM and other models
  - Precision measurements of radiative b decays allow probing of BSM physics
- LHCb is performing very well
  - World best results on  $\text{BR}(B^0 \rightarrow K^{*0}\gamma)/\text{BR}(B_s^0 \rightarrow \phi\gamma)$  and  $A_{\text{CP}}(B^0 \rightarrow K^{*0}\gamma)$

# Conclusions

- Photon polarization analysis in progress
- Untagged  $B_s^0$  effective lifetime measurement
  - Proper time acceptance function can be extracted from  $B_d \rightarrow K^{*0}\gamma$ 
    - Higher statistics  $\rightarrow$  smaller uncertainty
  - Sensitivity to  $A^\Delta$  around 0.4 for 2k signal events with the lifetime ratio (relative to  $B_d \rightarrow K^{*0}\gamma$ )
    - Expected to be  $\sim 0.2$  with the next data taking period
    - $< 0.1$  with the upgraded run ( $50\text{fb}^{-1}$ )

$$A^\Delta = \sin(2\psi) \cos\phi \quad \tan\psi = \frac{\bar{B} \rightarrow f^{CP} \gamma_R}{\bar{B} \rightarrow f^{CP} \gamma_L}$$

# Conclusions

- Theoretical input
  - Predictions of BSM models effect on the photon polarization
  - Other time dependent NP-sensible observables in radiative decays
    - Accesible with untagged decays?
- Moving forward!



**Thanks for your attention**

# Backup Slides

# Formulae

- $b \rightarrow s\gamma/g$  weak effective Hamiltonian in OPE

$$H_{eff} = \frac{-G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left( \sum_{i=1}^6 C_i \cdot O_i + C_{7\gamma} \cdot O_{7\gamma} + C_{8G} \cdot O_{8G} \right)$$