

Current Trends in Flavor Physics



29-31 March 2017 - Institut Henri Poincaré, Paris

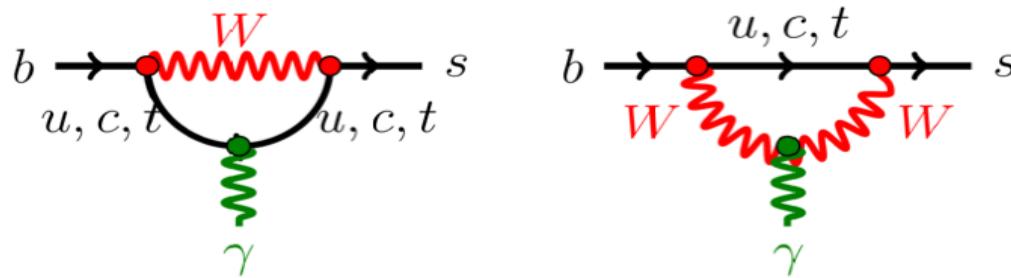
Radiative b-hadron decays at LHCb

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Radiative b transitions

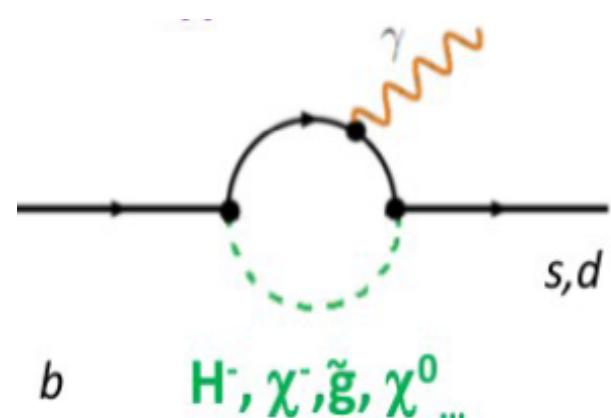
$b \rightarrow q \gamma$ ($q=d,s$) transition :

- first observed at Cleo (1993) through $B^{0,+} \rightarrow \gamma K^{*0,+}$
- FCNC electro-magnetic penguin



New physics affects the transition dynamics

BR, A_{CP} , Isospin asymmetry,
helicity structure of the photon



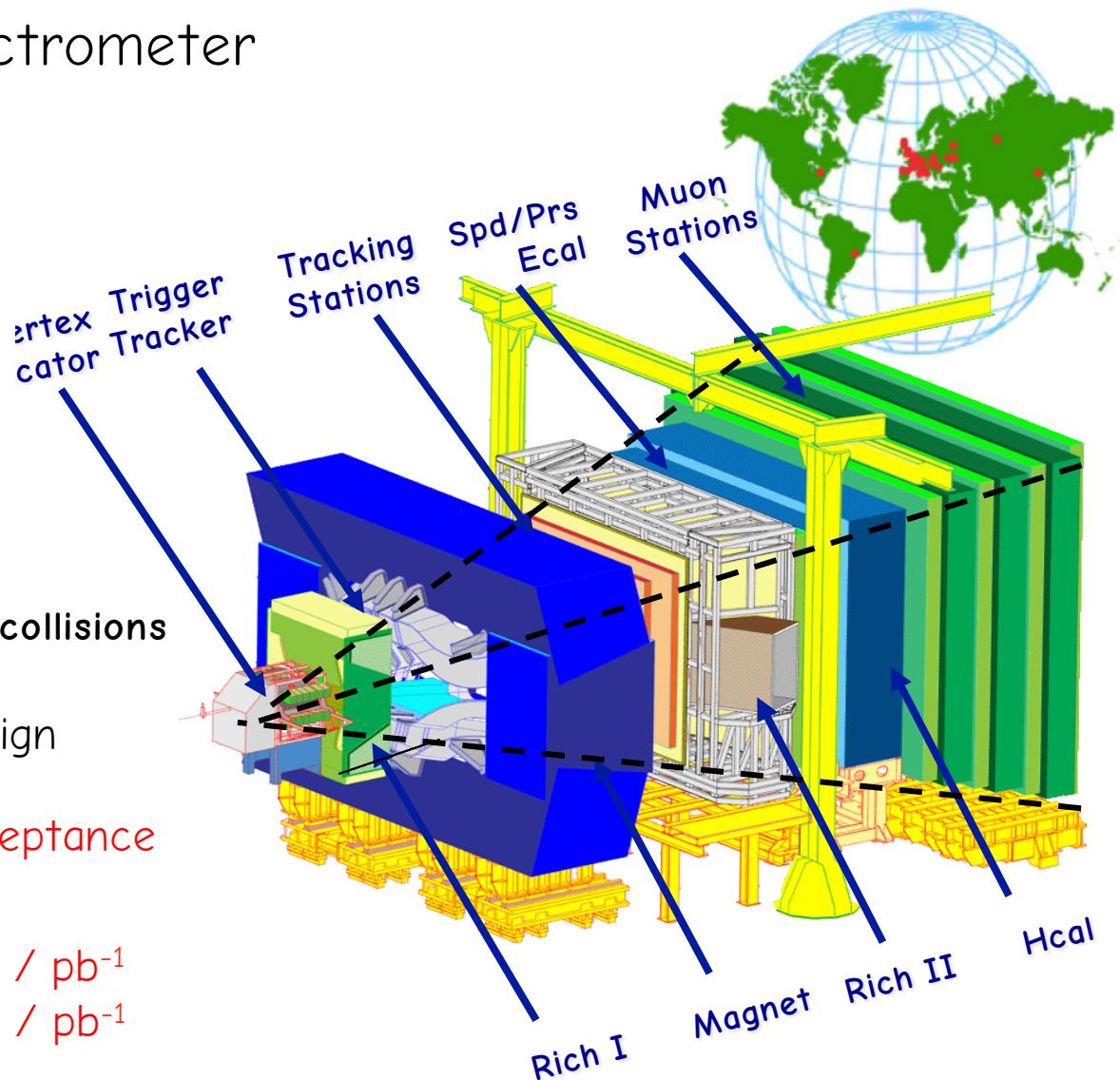
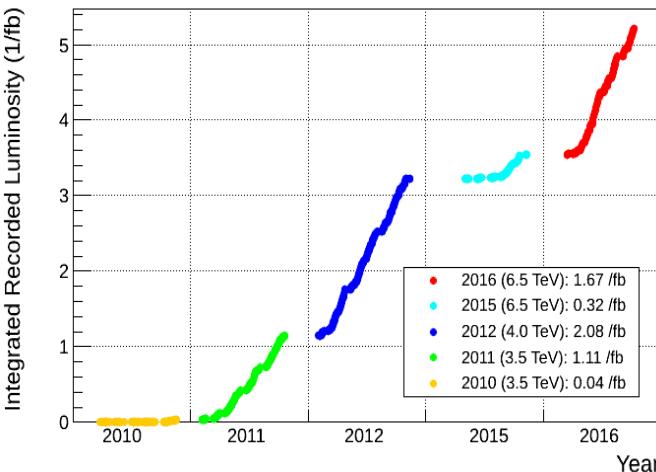


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The LHCb experiment

Single-arm forward spectrometer

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2016



- RUN 1 (2010-2013): 7/8 TeV pp collisions

Visible pp interaction/crossing: $O(1.5)$

factor 4 beyond the design

Integrated luminosity: 3fb^{-1}

$\sim 2 \times 10^{11} \text{ bb}$ in LHCb acceptance

Radiative decay reconstruction rate

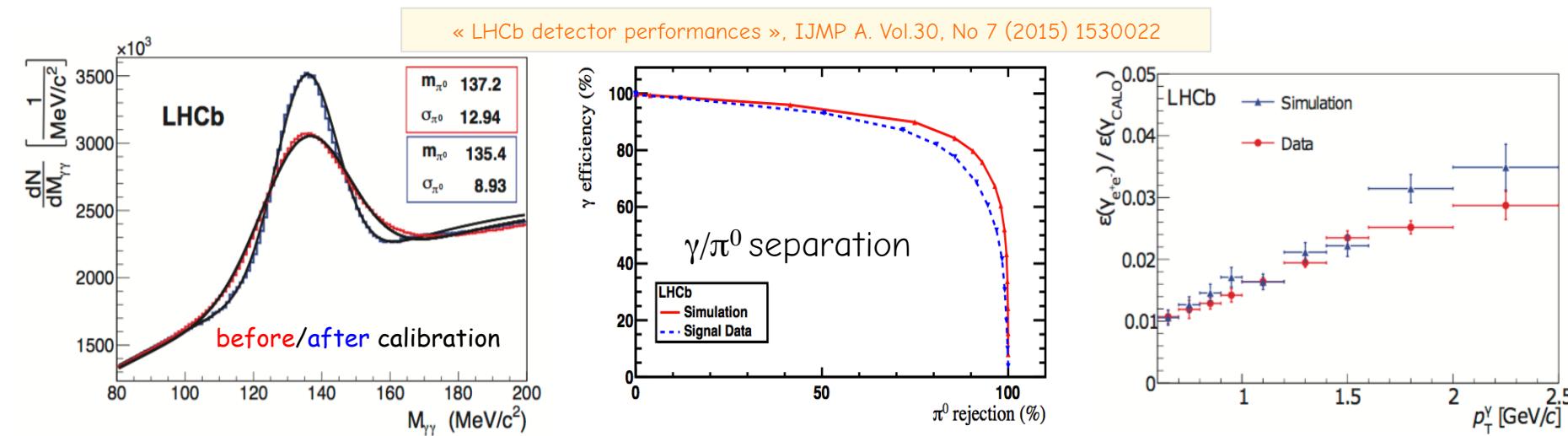
$B^0 \rightarrow K^{*0} \gamma$: $\sim 7 \text{ events / pb}^{-1}$

$B_s \rightarrow \phi \gamma$: $\sim 1 \text{ events / pb}^{-1}$

- RUN 2 (2015-2018): 13 TeV pp collisions

Photon reconstruction @ LHCb

- Calorimetric photons: unconverted photons or conversion after magnet
=> from calorimeters deposit
- Di-electron photons: conversion before magnet
=> from tracking system
- Large calorimeter occupancy : large combinatorial background
=> neutralID to separate neutral EM showers from hadronic and electrons deposits
- Above $p_T \sim 2.5$ GeV/c π^0 likely produced a single Ecal cluster
=> those π^0 represents an important background to high energy photons
=> γ/π^0 separation multivariate



Radiative decay anatomy

Due to trigger constraint and large combinatorics
the radiative decays mostly rely on high pT photons

LO threshold in 2011(2012) : $E_T(\gamma) > 2.5$ (3.0) GeV

Typical trigger efficiency on radiative modes $\sim 30\text{-}40\%$

For comparison : (di)muon channel $\epsilon_{\text{trg}} \sim 80\text{-}90\%$

Mass resolution driven by calorimeter resolution :

$$\sigma_M(B \rightarrow X \gamma) \sim 90 \text{ MeV}/c^2$$

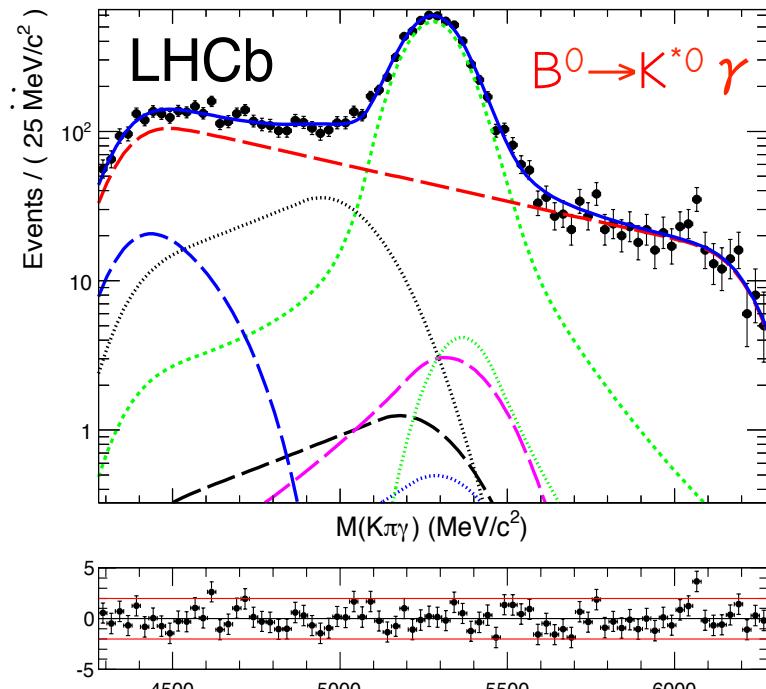
$$\text{For comparison : } \sigma_M(B \rightarrow hh) \sim 25 \text{ MeV}/c^2$$

$$\sigma_M(B \rightarrow J/\psi X) \leq 10 \text{ MeV}/c^2$$

No constraint on vertexing from γ / large photon multiplicity / limited mass resolution :

Large combinatorial background
partially rec'ed and peaking backgrounds

Tight selections are applied



- Generic background contamination :
 - Combinatorial background
 - Partially reconstructed $b \rightarrow s \gamma$ decays
 - Partially reconstructed $b \rightarrow c$ ($X + hh\pi^0$)
- Specific peaking backgrounds :
 - Charmless $B_{d,s} \rightarrow h^+h^- \pi^0$
 - Irreducible $b \rightarrow d \gamma$: $B_s \rightarrow K^{*0} \gamma$
 - b -baryons cross-feed $\Lambda_b \rightarrow \Lambda^*(K^-p) \gamma$



Run 1 achievements

- Do checklist
- Post Checklist
- Cross off Checklist
- Something Else



B \rightarrow V γ measurements

B \rightarrow V γ measurements

BR \rightarrow V γ measurements

B_s \rightarrow $\phi\gamma$ branching fraction

$$\begin{aligned} \text{BR}(B^0 \rightarrow K^{*0}\gamma) &= (4.33 \pm 0.15) \times 10^{-5} & [\text{Belle, Babar, Cleo}] \\ \text{BR}(B_s \rightarrow \phi\gamma) &= (5.7^{+2.1}_{-1.8}) \times 10^{-5} & [\text{Belle}] \end{aligned}$$

SM-predictions

large hadronic uncertainty mostly canceling in the ratio :

[Ali, Pecjak, Greub, 2008]

$$\text{BR}(B^0 \rightarrow K^{*0}\gamma) / \text{BR}(B_s \rightarrow \phi\gamma) = 1.0 \pm 0.2$$

LHCb result (1.0 fb $^{-1}$ - 2011 data)

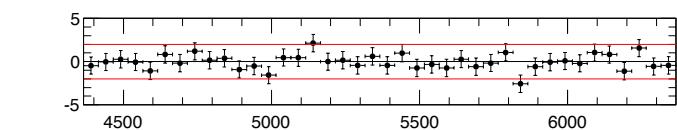
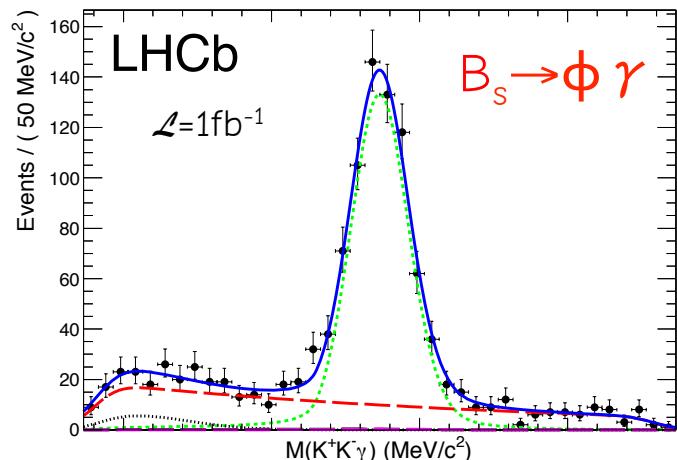
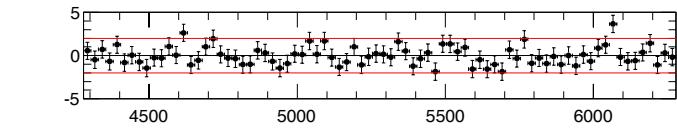
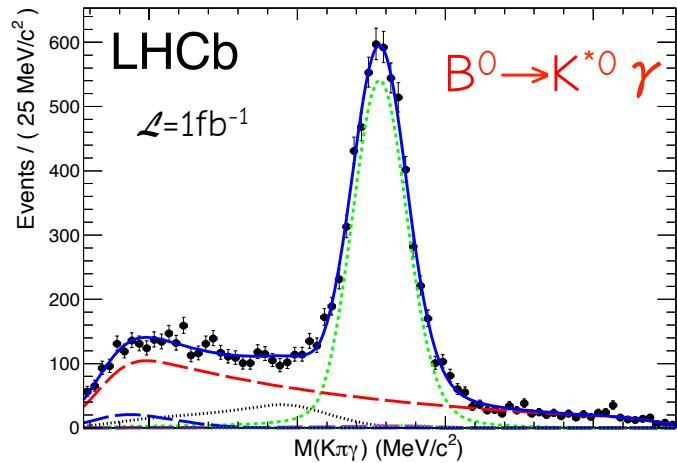
[Nuclear Physics B, 867, 1-18 (2013)]

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

$$\mathcal{B}(B_s^0 \rightarrow \phi\gamma) = (3.5 \pm 0.4) \times 10^{-5}$$

Main systematics

- dominated by f_s/f_d : 8%
- reconstruction & selection : 2%
- background model : 2%





B \rightarrow V γ measurements

B \rightarrow V γ

шанс на успех

Direct CP asymmetry in B $^0\rightarrow$ K $^{*0}\gamma$

SM-prediction :

Phys. Rev. D72 (2005) 014013

$$A_{CP} = -0.0061 \pm 0.0043$$

A_{CP} enhanced in NP scenarii

B-factory measurement

BABAR, Phys. Rev. Lett. 84, 5283–5287

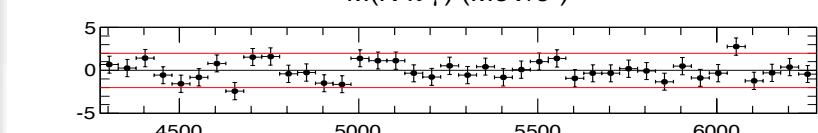
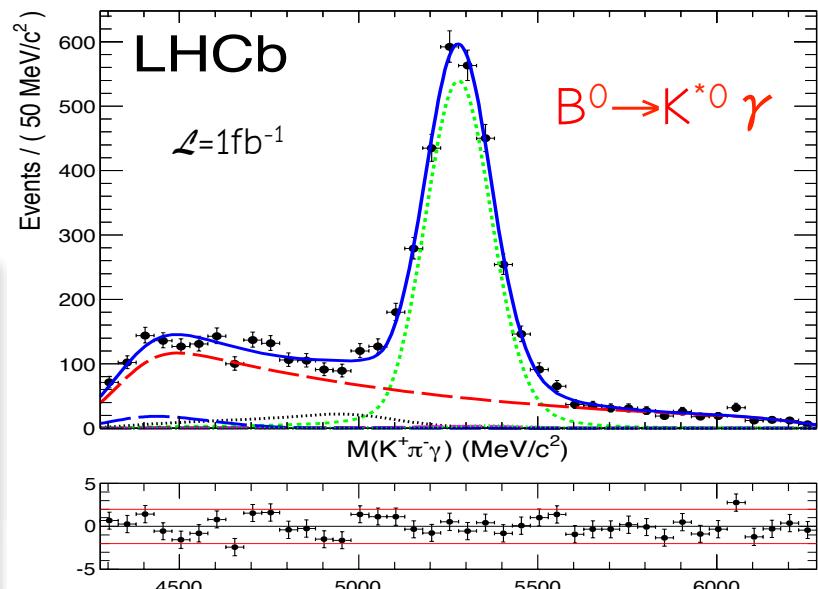
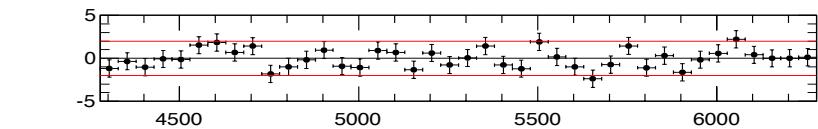
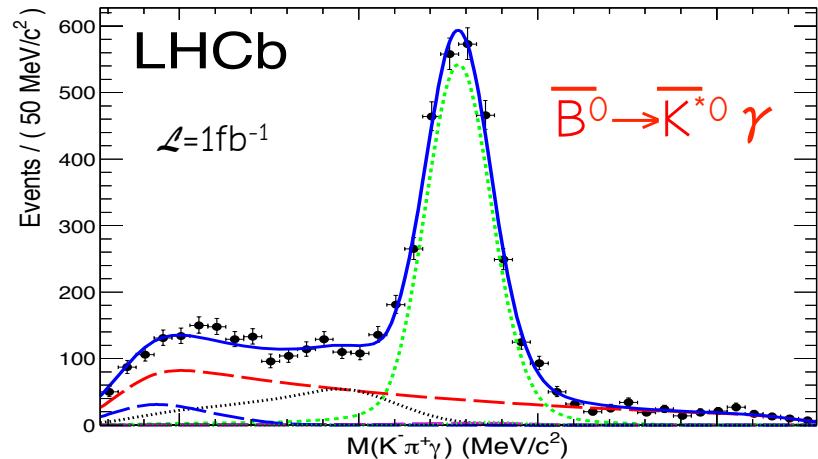
$$A_{CP} = -0.016 \pm 0.022 \pm 0.007$$

LHCb result (1.0 fb $^{-1}$ - 2011 data) :

$$N_{B^0} + N_{\bar{B}^0} = 5300 \pm 100$$

Nuclear Physics B, 867, 1-18 (2013)

$$A_{CP}(B^0 \rightarrow K^{*0}\gamma) = 0.008 \pm 0.017(stat) \pm 0.009(syst)$$



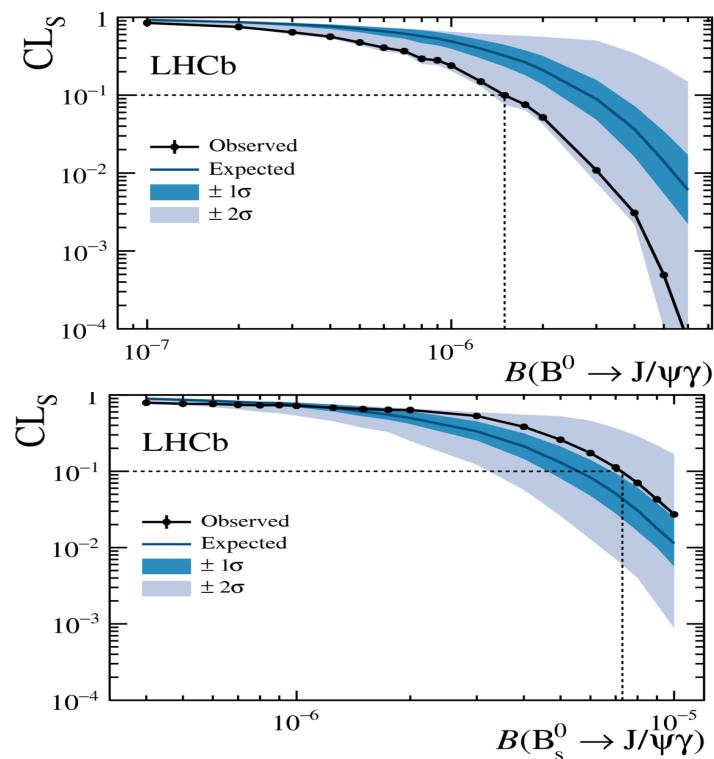
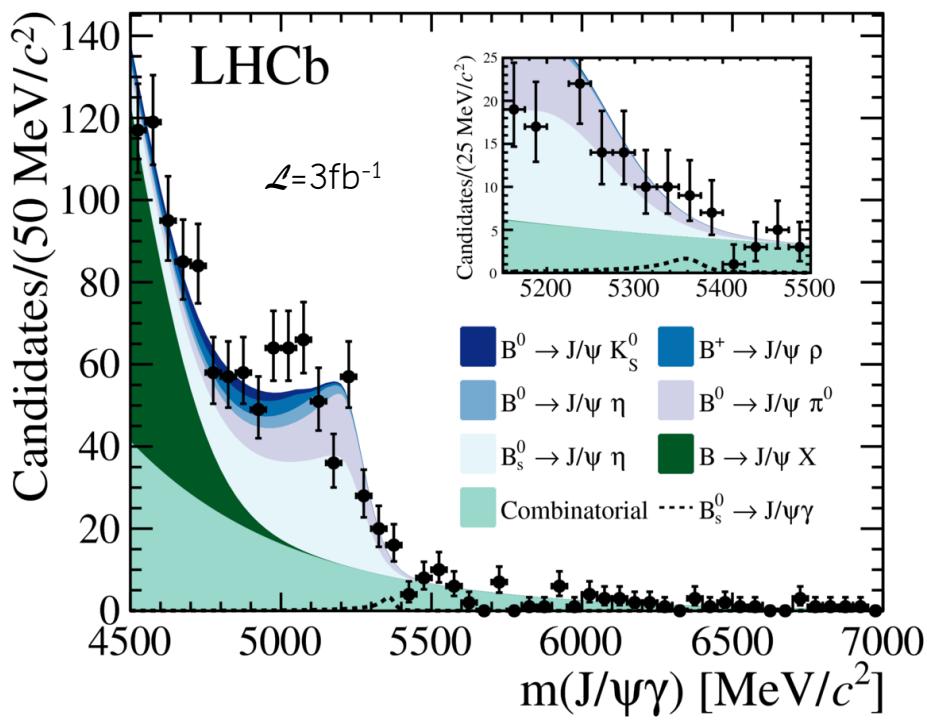
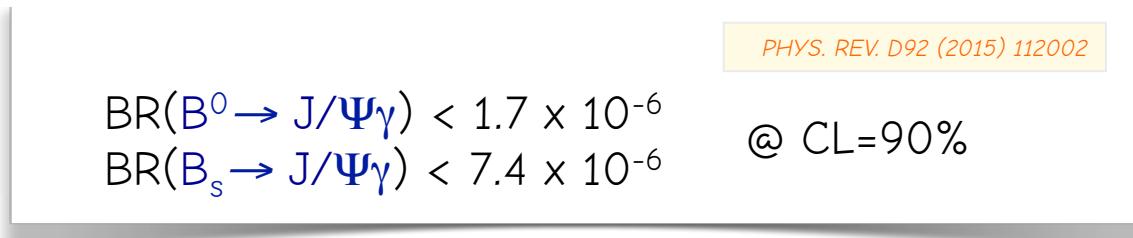


B \rightarrow V γ measurements

B \rightarrow V γ measurements

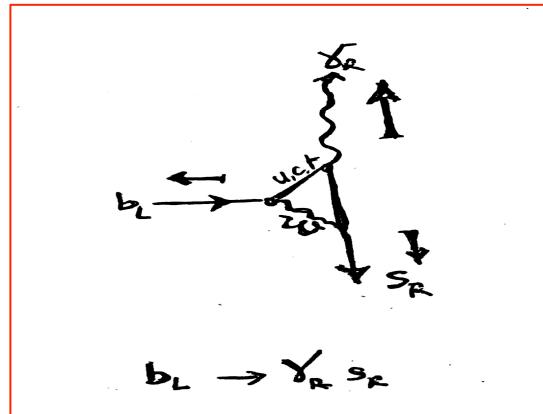
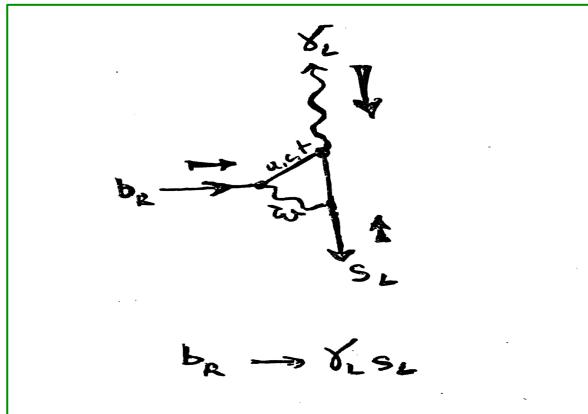
Search for B $^0 \rightarrow J/\Psi\gamma$ & B $_s \rightarrow J/\Psi\gamma$

Not a radiative penguin transitions but share the same final-state problematics



Photon polarisation

- Real photon ($h=\pm 1$) implies the helicity flip on the quark lines
- SM : EW-penguin dominates the $b \rightarrow q\gamma$ transition
 - W-coupling to left-handed quarks \Rightarrow transition through helicity violation $\sim m_q$



- Leading (EM dipole) operator in the effective Hamiltonian approach :

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

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

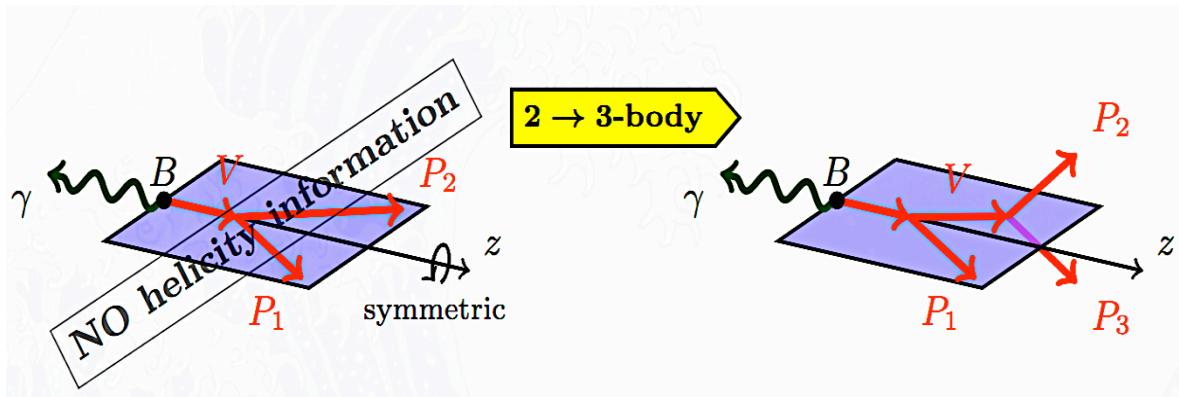
- other SM operator contributions (O_2, \dots) : $A_R/A_L \sim \text{few \%}$

Right-handed component could be enhanced in NP models

Photon polarisation

Experimentally, the photon polarization can be extracted from ...

- angular analysis of the recoil 3-body in the $B \rightarrow \gamma + (\text{hhh})_{\text{res}}$ decay mode

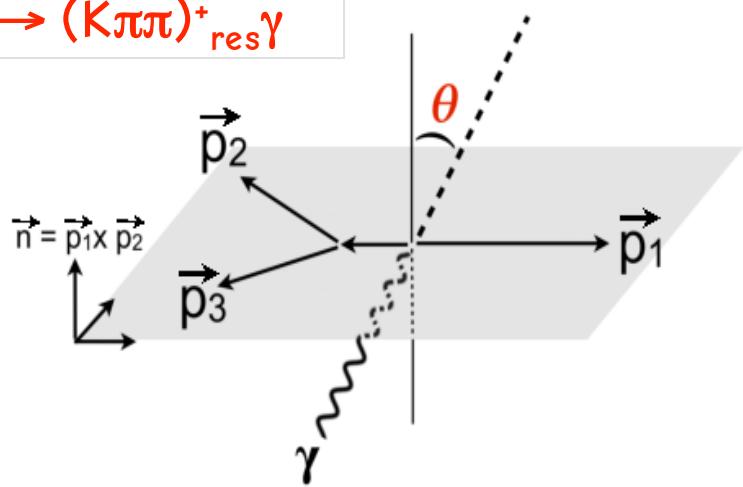


- time-dependent analysis of the $B \rightarrow \gamma \Phi_{\text{CP}}$ decay modes
- di-lepton angular analysis at low q^2 of the (virtual) photon decay in $B \rightarrow V e^+ e^-$
- angular analysis in the radiative transition of b-baryons



¹² Helicity structure in $B \rightarrow (K\pi\pi)_{\text{res}}\gamma$

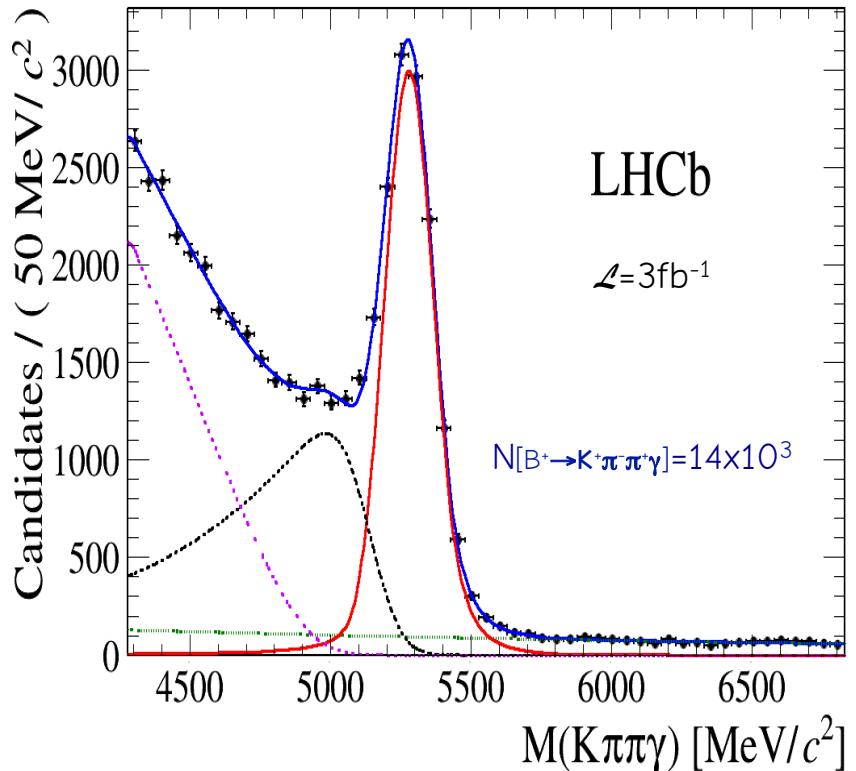
$B^+ \rightarrow (K\pi\pi)^+_{\text{res}}\gamma$



For a mixture of spin-parity $K_{\text{res}}(1^+, 2^+, 1^-)$:

$$\frac{d\Gamma}{ds ds_{13} ds_{23} d\cos\theta} \propto$$

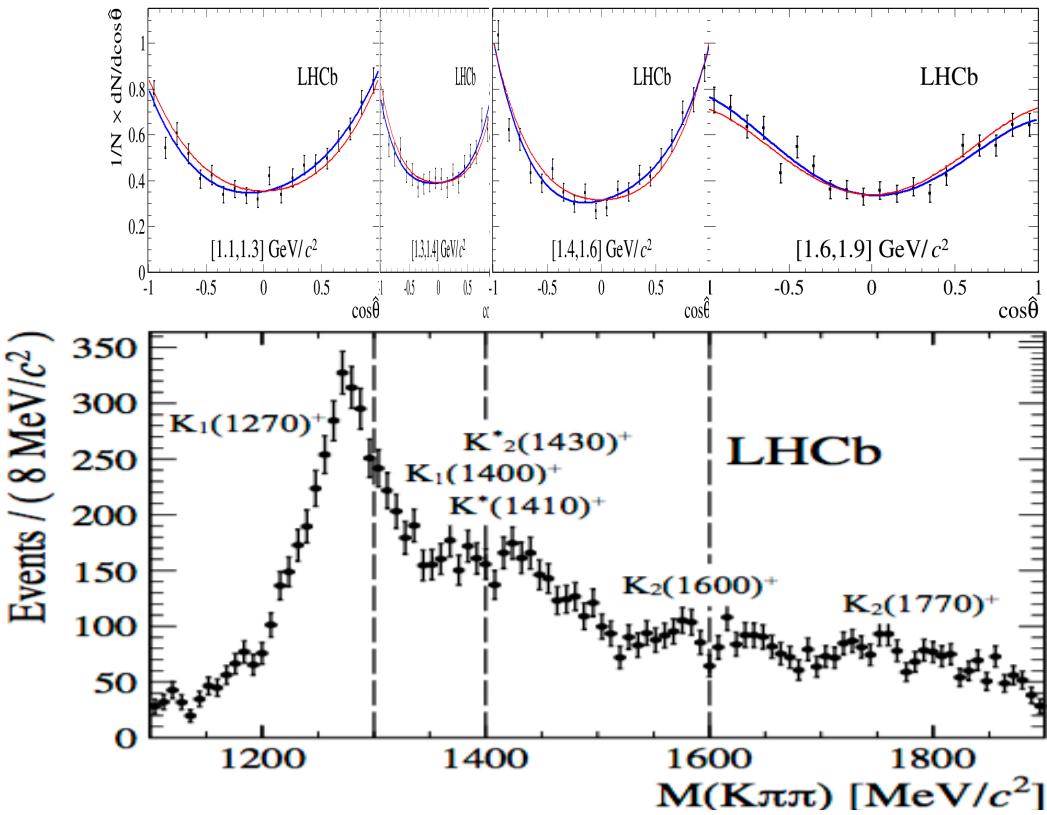
$$\sum_{i=0,2,4} a_i(s, s_{13}, s_{23}) \cos^i \theta + \lambda_\gamma \sum_{j=1,3} a_j(s, s_{13}, s_{23}) \cos^j \theta$$



Up-down photon asymmetry is proportional to the photon polarisation λ_γ
 Angular analysis of photon direction wrt to $(K\pi\pi)_{\text{res}}$ decay plane in different mass bins

LHCb

13 Helicity structure in $B \rightarrow (K\pi\pi)_{\text{res}}\gamma$



[Phys. Rev. Lett. 112, 161801 (2014)]

*Photons from radiative decays
are polarized @ 5.2 σ
significance*

*First direct observation of photon
polarization in $b \rightarrow s\gamma$ transition*

as a by-product:

LHCb-CONF-2013-009

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

Measuring the λ_γ value from the up-down asymmetry require to separate the $(K\pi\pi)$ resonances & theoretical determination of the helicity amplitude

Phys. Rev. Lett. 88 (2002) 051802

e.g. for a single 1+ resonance

$$\frac{d\Gamma(B \rightarrow K\pi\pi\gamma)}{ds ds_{13} ds_{23} d\cos\theta} \propto \frac{1}{2} |\vec{\mathcal{J}}|^2 (1 + \cos^2\theta) + \lambda_\gamma \cos\theta \text{Im}[\vec{n} \cdot (\vec{\mathcal{J}} \times \vec{\mathcal{J}}^*)]$$

LHCb

Virtual photon : $B^0 \rightarrow K^{*0} e^+ e^-$

$B^0 \rightarrow K^*(\gamma^* \rightarrow ee)$ in the low q^2 region

Branching fraction in [30 ; 1000] MeV/c²

1.0 fb⁻¹ - 2011 data :

J. High Energy Phys. 05 (2013) 159

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

Full angular analysis in [20; 1120]MeV/c²

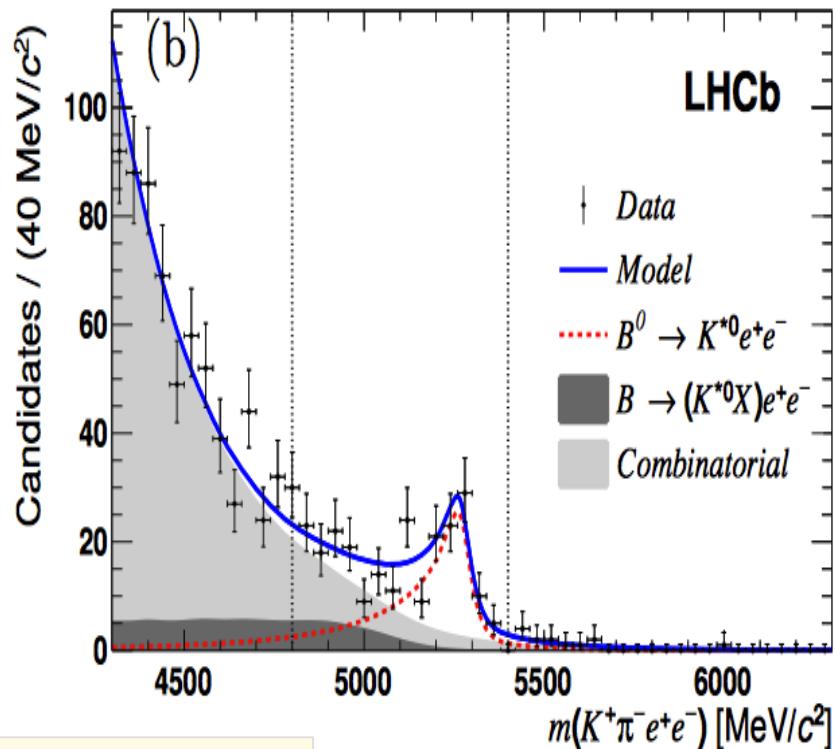
3.0 fb⁻¹ – 2011+2012 data :

$$F_L = 0.16 \pm 0.06 \pm 0.03$$

$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$

$$A_T^{\text{Im}} = +0.14 \pm 0.22 \pm 0.05$$

$$A_T^{\text{Re}} = +0.10 \pm 0.18 \pm 0.05,$$



Related to the
photon polarisation



Time-dependent decay rate

Direct access via the time-dependent decay rate of $B \rightarrow \Phi^{CP}\gamma$

$$\Gamma_{B(\bar{B})^0_s \rightarrow \Phi^{CP}\gamma}(t) = |A|^2 e^{-\Gamma_{(s)} t} \left[(\cosh(\Delta\Gamma_{(s)} t/2) + \mathcal{A}_\Delta \sinh(\Delta\Gamma_{(s)} t/2)) \pm \mathcal{C}_{CP} \cos(\Delta m_{(s)} t) \mp \mathcal{S}_{CP} \sin(\Delta m_{(s)} t) \right]$$

untagged / *tagged analysis required*

$$\mathcal{S}_{CP} \sim \sin 2\psi \sin \phi_{(s)}$$

$$\mathcal{A}_\Delta \sim \sin 2\psi \cos \phi_{(s)}$$

$$\tan \psi = \left| \frac{\mathcal{A}_R}{\mathcal{A}_L} \right|$$

$\phi_{(s)}$ is the mixing-decay weak phase

$B_s \rightarrow \phi \gamma$: ϕ_s (SM) $\sim 2\beta_s - 2\beta_s$	~ 0
$B_d \rightarrow K^{*0}\gamma$: ϕ_d (SM) $\sim 2\beta - 2\beta_s$	$\sim 2\beta$
$B_d \rightarrow \rho^0\gamma$: ϕ_d (SM) $\sim 2\beta - 2\beta$	~ 0

- **B^0 decays** : sensitive to the polarisation through the TD asymmetry term \mathcal{S}_{CP}
Out of LHCb reach for the main decay mode $B^0 \rightarrow K_s \pi^0 \gamma$
No sensitivity to A_Δ ($\Delta\Gamma_d \sim 0$)

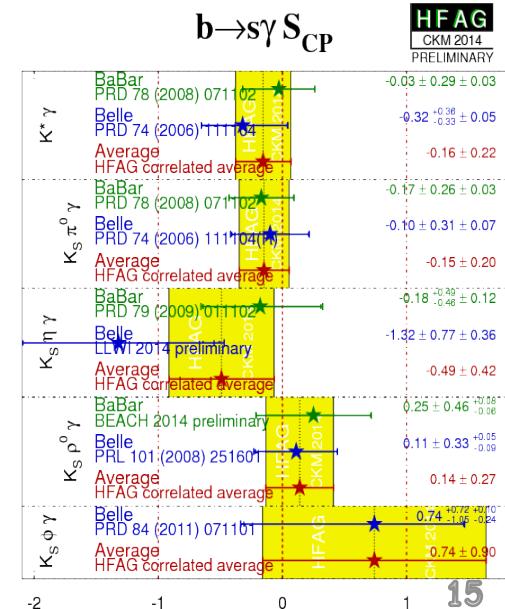
$[B^0 \rightarrow K_s \pi^0 \gamma]$ is part of Boris PhD]

- **B_s decays** : sensitive through the mixing term \mathcal{A}_Δ
 - $\Delta\Gamma_s / \Gamma_s \sim 10\%$
 - untagged analysis

Muheim et al., PLB664(08)17

SM: $A_\Delta = 0.047 \pm 0.025 \pm 0.015$

Left-Right Symmetric model: $\mathcal{A}_{LRSM}^\Delta \sim 0.7$





Time-dependent decay rate

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)



CERN-EP-2016-210
LHCb-PAPER-2016-034
September 7, 2016

First experimental study of photon polarization in radiative B_s^0 decays

The LHCb collaboration

Abstract

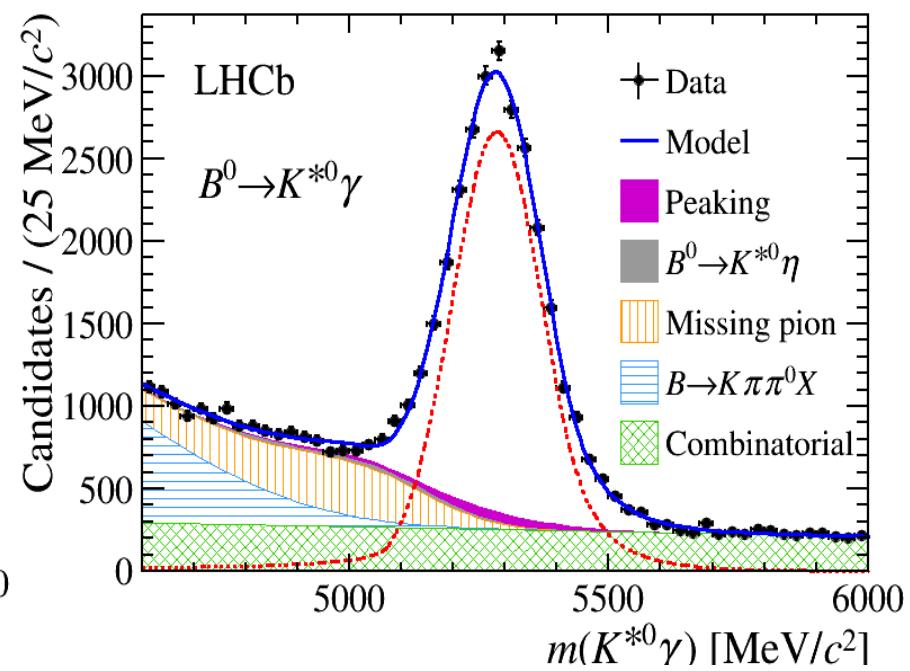
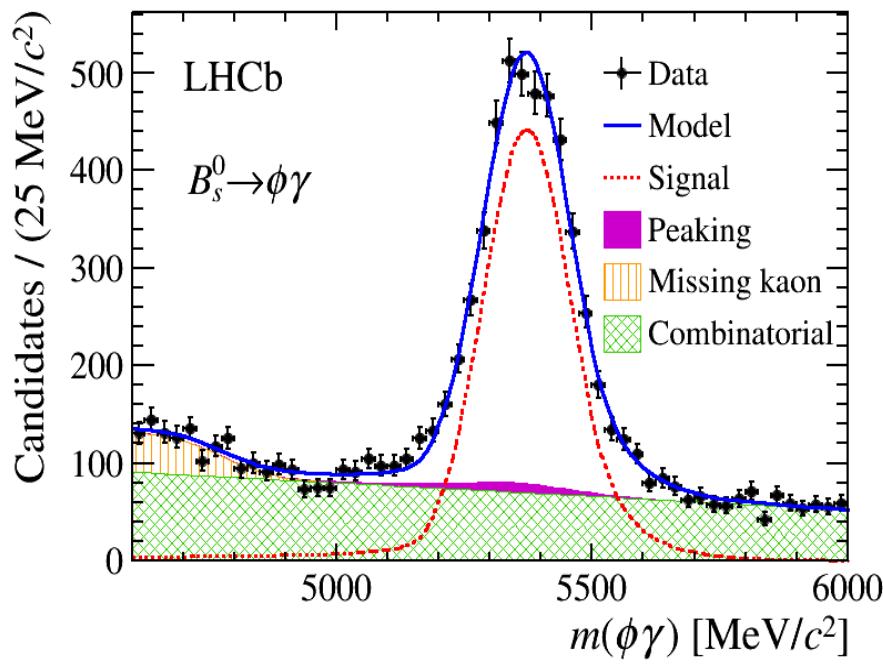
The polarization of photons produced in radiative B_s^0 decays is studied for the first time. The data are recorded by the LHCb experiment in pp collisions corresponding to an integrated luminosity of 3 fb^{-1} at center-of-mass energy $\sqrt{s} = 7\text{ TeV}$. A time-dependent analysis of the $B_s^0 \rightarrow \phi\gamma$ decay rate is performed, where the parameter A^Δ , which is related to the ratio of the two radiative decay polarization amplitudes in $b \rightarrow s\gamma$ transitions, is measured. This result is consistent with the Standard Model prediction within two standard deviations.

$$A^\Delta = -0.98^{+0.46}_{-0.52}(\text{stat.})^{+0.23}_{-0.20}(\text{syst.})$$

Submitted to Phys. Rev. Lett.

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$B_s \rightarrow \phi\gamma$ signal extraction



Signal	dashed red line	N events	4214 ± 90
		$\mu (\text{MeV}/c^2)$	5371.88 ± 1.89
		$\sigma (\text{MeV}/c^2)$	86.31 ± 1.97

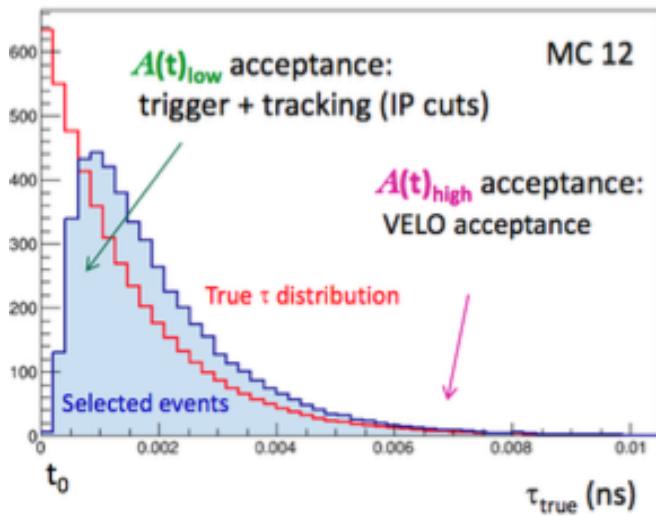
Signal	dashed red line	N events	25760 ± 301
		$\mu (\text{MeV}/c^2)$	5284.07 ± 0.85
		$\sigma (\text{MeV}/c^2)$	87.83 ± 0.95

$B_s \rightarrow \phi\gamma$ propertime analysis

- Propertime PDF:

$$\mathcal{P}(t) = [\text{Physics} \times \text{Acceptance}] \otimes \text{Resolution}$$

- Acceptance $A(t)_{\text{low}} \times A(t)_{\text{high}}$: trigger, tracking, reconstruction and selection requirements



- Parameterization of the acceptance using function $A(t)$:

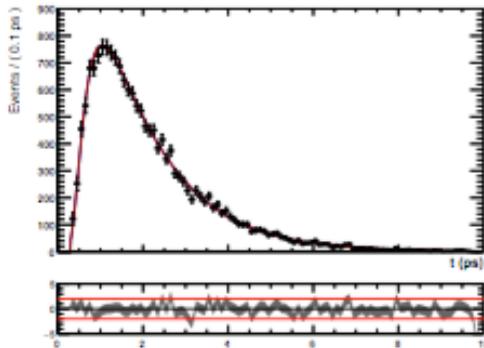
$$A(t) = \frac{[a(t - t_0)]^n}{1 + [a(t - t_0)]^n} \times e^{-\delta \Gamma t}$$

$A(t)_{\text{low}}$ $A(t)_{\text{high}}$

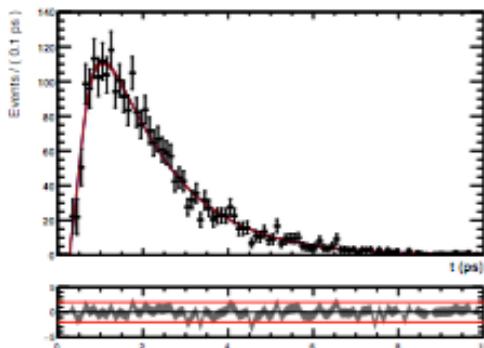
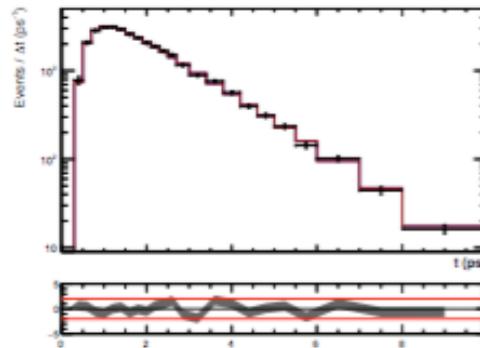
- Key in the photon polarization measurement;
- Need to be precisely determined/controlled.

Propertime fit

- Background-subtracted sample (sWeight method)



(a) $B^0 \rightarrow K^{*0} \gamma$



(b) $B_s^0 \rightarrow \phi \gamma$

Parameter	Fitted value
Acceptance from MC	
a	$1.870 \pm 0.041 \text{ ps}^{-1}$
n	2.23 ± 0.10
$t_0(B^0 \rightarrow K^{*0} \gamma)$	$184 \pm 14 \text{ fs}$
$\Delta t_0(B_s^0 \rightarrow \phi \gamma)$	$-11.7 \pm 3.4 \text{ fs}$
$\delta\Gamma(B^0 \rightarrow K^{*0} \gamma)$	$39.5 \pm 3.6 \text{ ns}^{-1}$
$\Delta\delta\Gamma(B_s^0 \rightarrow \phi \gamma)$	$-2.3 \pm 3.5 \text{ ns}^{-1}$

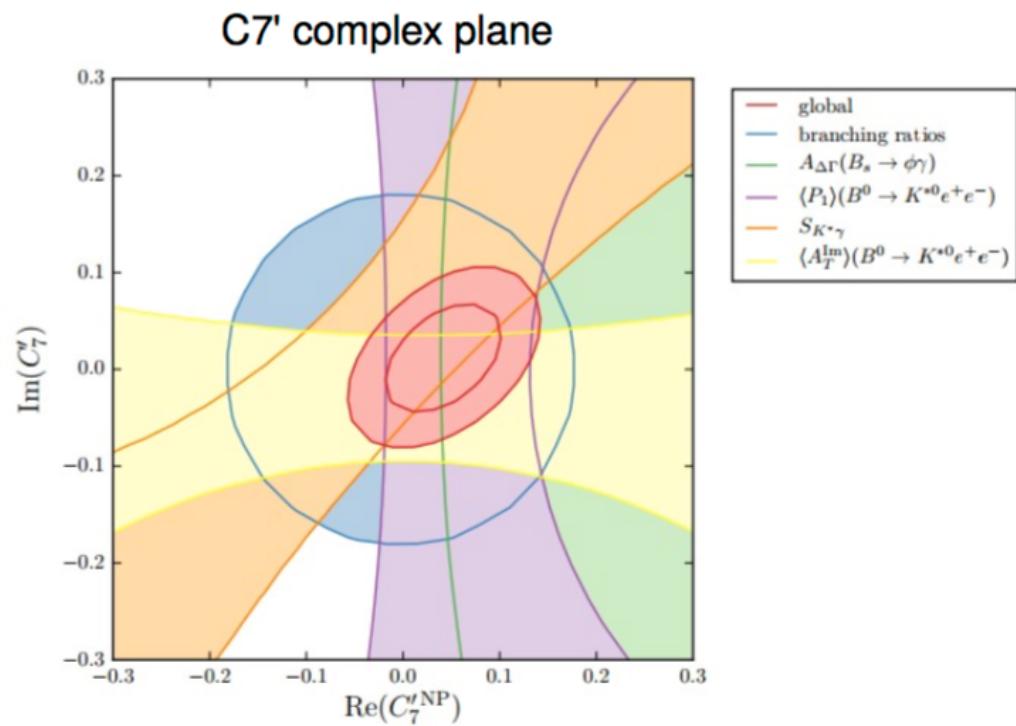
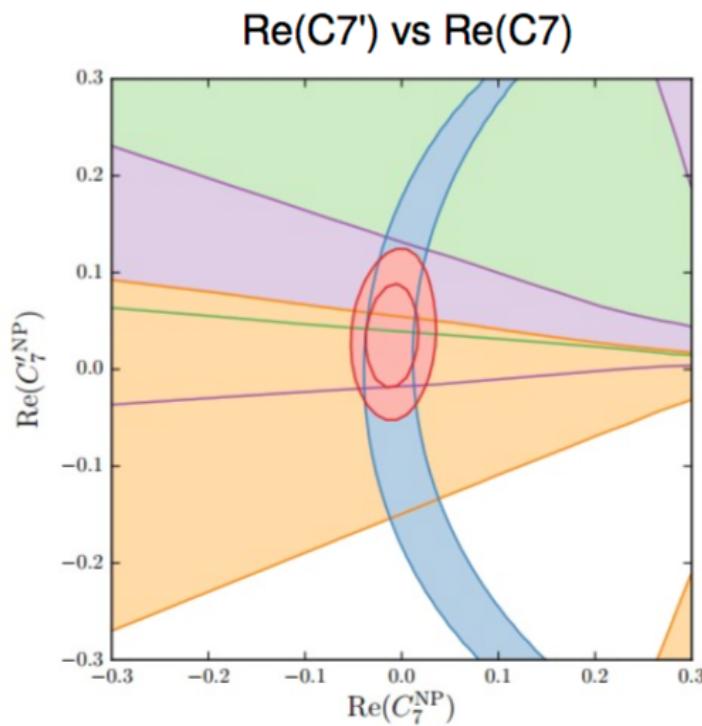
Parameter	Data-MC difference
$\Delta t_0(B^0 \rightarrow K^{*0} \gamma \text{ Data})$	$15.0 \pm 5.1 \text{ fs}$
$\Delta\delta\Gamma(B^0 \rightarrow K^{*0} \gamma \text{ Data})$	$5.1 \pm 6.0 \text{ ns}^{-1}$

Parameter	Average
$\Delta\Gamma_s$	$0.083 \pm 0.006 \text{ ps}^{-1}$
Γ_s	$0.6643 \pm 0.0020 \text{ ps}^{-1}$
Γ_d	$0.6579 \pm 0.0017 \text{ ps}^{-1}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	-0.239

$$\mathcal{A}^\Delta = -0.98 \begin{array}{l} +0.46 \\ -0.52 \end{array} (\text{stat.}) \begin{array}{l} +0.23 \\ -0.20 \end{array} (\text{syst.})$$

Interpretation

C7 constraints from radiative measurements



Reference: Constraints on new physics from radiative B decays (A. Paul, D. M. Straub)



Prospective Students





Prospective SUSY

The expectedly large run2 statistics will allow to explore suppressed radiative modes

- e.g. V_{td} suppressed $b \rightarrow d\gamma$ penguin

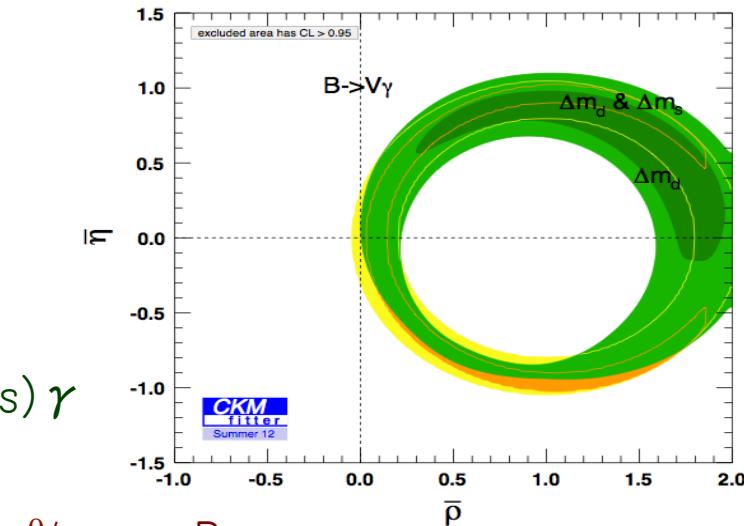
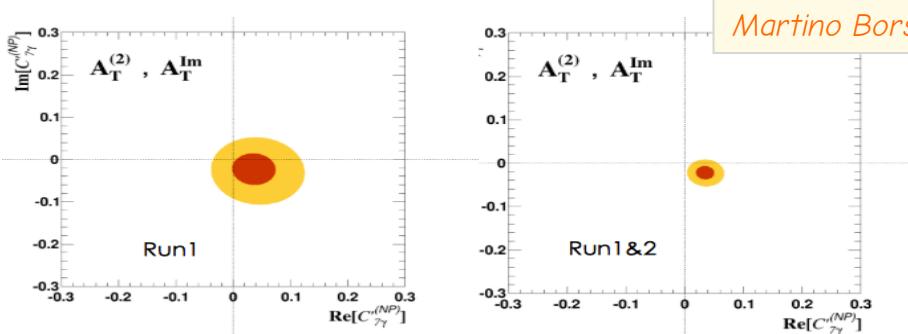
Branching ratio & asymmetry of exclusive $b \rightarrow (d + s)\gamma$ modes provide a direct constraint on UT

Such transition could be accessible in LHCb via $B^0 \rightarrow \rho^0/\omega\gamma$, $B^+ \rightarrow a_1^+\gamma$

Could separate the $b \rightarrow d\gamma$ transition $B_s \rightarrow K^*\gamma$ from $b \rightarrow s\gamma$ in B^0 using converted photons

- Photon polarisation : reach < 10 % resolution

scenario II: $C_{7\gamma}^{(NP)} = 0$, $C'_{7\gamma}^{(NP)} \in \mathbb{C}$



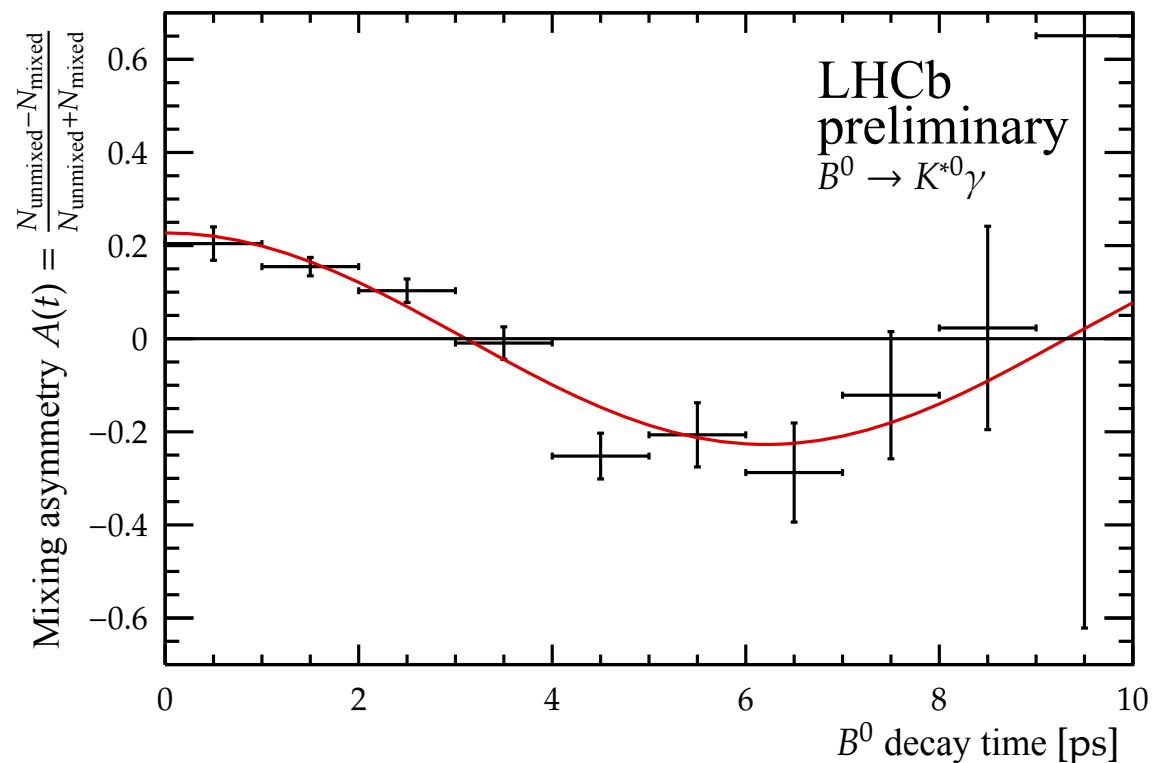
Prospective from K^*ee
angular analysis

- Photon polarisation (cont')

Enhanced sensitivity in neutral B decays from tagged analysis giving access to TD asymmetries

For illustration :

LHCb tagging performance applied for the first time on a radiative decay



Photon reconstruction @ LHCb

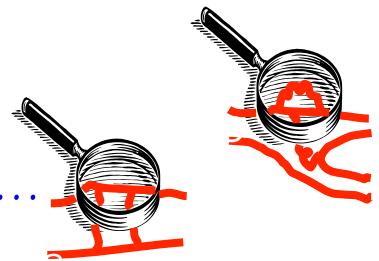
Because of trigger constraints and the hadronic environment, some radiative channels are out of reach for LHCb

- What LHCb can do (or has already done) :
 - $(h^+h^-)\gamma$ channels from $b \rightarrow s\gamma$ transition of neutral b-hadrons : B^0, B_s, Λ_b
 - $(h^+h^-h^+)\gamma$ channel from charged b-hadrons
 - Same using converted photons $\gamma \rightarrow ee$
 - Same for suppressed $b \rightarrow d\gamma$ transitions when accumulating statistics
- What LHCb could probably do :
 - $(h^+h^-\pi^0)\gamma, (h^+h^-K_s)\gamma$: e.g. $K_1^0\gamma, B \rightarrow \omega\gamma$
 - $B^+ \rightarrow K^{*+}(K_s\pi^+)\gamma$: e.g. isospin asymmetry in $K^*\gamma$
 - $\Lambda_b \rightarrow \Lambda_{1115}\gamma$: very challenging
- What LHCb can't do
 - $B^+ \rightarrow K^{*+}(K^+\pi^0)\gamma$ and a fortiori $B^+ \rightarrow \rho^+(\pi^+\pi^0)\gamma$
 - $B^0 \rightarrow K^{*0}(K_s\pi^0)\gamma$: time-dependent asymmetry in radiative $B^0 \rightarrow K^{*0}\gamma$
 - inclusive $b \rightarrow X_s\gamma$ BR

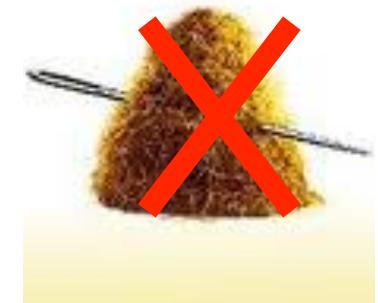
Conclusions

LHCb provides an unique laboratory for precise measurements in radiative decay

Great harvest of result with 2011-2012 Run 1
World best measurements in radiative $V\gamma$ decays ...



... consistent with SM expectation



Many updated or new results incl. run2 data expected soon





$B_s \rightarrow \phi\gamma$ Branching Fraction

- Systematic uncertainty dominated by f_s/f_d ($\pm 8\%$)

[*Phys. Rev. D* 85 (2012) 032008]

from semi-leptonic $B_{u,d,s} \rightarrow D_{(s)} \mu^- \nu \chi$ and hadronic $B_{u,d,s} \rightarrow D_{(s)} h$

$$\frac{f_s}{f_d} = 0.267^{+0.021}_{-0.020}$$

- Background model ($\pm 2\%$)

Contamination level and shape

- Reconstruction and selection ($\pm 2\%$)

Trigger and selection efficiencies, Particle reconstruction & identification

Update with whole 3fb^{-1} sample ongoing

both statistical and systematical uncertainty will improve
(more precise f_s/f_d , improved background model ...)



A_{CP} in $B^0 \rightarrow K^{*0} \gamma$

$\sqrt{C}\bar{b} \rightarrow D \rightarrow K$

- $K^+ \pi^- / K^- \pi^+$ detection asymmetry

From charm $D^0 \rightarrow K \pi$ large control sample

$$A_D(K\pi) = \frac{\varepsilon(K^-\pi^+) - \varepsilon(K^+\pi^-)}{\varepsilon(K^-\pi^+) + \varepsilon(K^+\pi^-)} = (-1.0 \pm 0.2)\%$$

LHCb-CONF-2011-042.

- B production asymmetry

From large $B \rightarrow J/\psi K^$ sample*

$$A_p(B) = \frac{R(\bar{B}) - R(B)}{R(\bar{B}) + R(B)} = (1.0 \pm 1.3)\%$$

- Background model

$$\Delta A_{CP} = (-0.2 \pm 0.7)\%$$

Contamination level, shape & CP asymmetry in various background components

Dominated by the unknown asymmetry from the misidentified $\Lambda_b \rightarrow (pK)\gamma$ contamination

- Detector non-uniformity

$$\Delta A_{CP} = (+0.1 \pm 0.2)\%$$

Possible detector bias strongly reduced by switching regularly the magnet polarity

Update with whole 3fb^{-1} sample ongoing

both statistical and systematical uncertainty will improve :
more precise detection and production asymmetry,
CP asymmetry from background in particular $\Lambda_b \rightarrow (pK)\gamma$

$B_s \rightarrow \phi\gamma$ propertime analysis

● Analysis :

- Unbinned maximum likelihood fit of the $B_s \rightarrow \phi(K^+K^-)\gamma$ propertime
- use $B^0 \rightarrow \phi(K^+\pi^-)\gamma$ as control channel (simultaneous fit)
- Based on run1 data (2011-2012) : int. lum. 3fb^{-1}

$$\mathcal{B}(B^0 \rightarrow K^{*0}\gamma) = (4.33 \pm 0.15) \times 10^{-5}$$

$$\mathcal{B}(B_s \rightarrow \phi\gamma) = (3.5 \pm 0.4) \times 10^{-5} \text{ (LHCb, 2011)}$$

● Selection :

- Kinematical criteria : high-pT photon, invariant masses, track quality ...
- Topological criteria : high-IP tracks, displaced 2ndary vertex, vertex quality,
- PID criteria : photon ID, Kaon/pion ID

● Large background contamination:

- Combinatorial
- Partially reconstructed : eg. $B \rightarrow K^+ h h \gamma$
- "cross-feed" due to track misID (e.g. $\Lambda_b \rightarrow p K^- \gamma$) or π^0/γ ($B \rightarrow h h \pi^0$)