# SUSY 2016

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# Radiative b-hadron decays at LHCb

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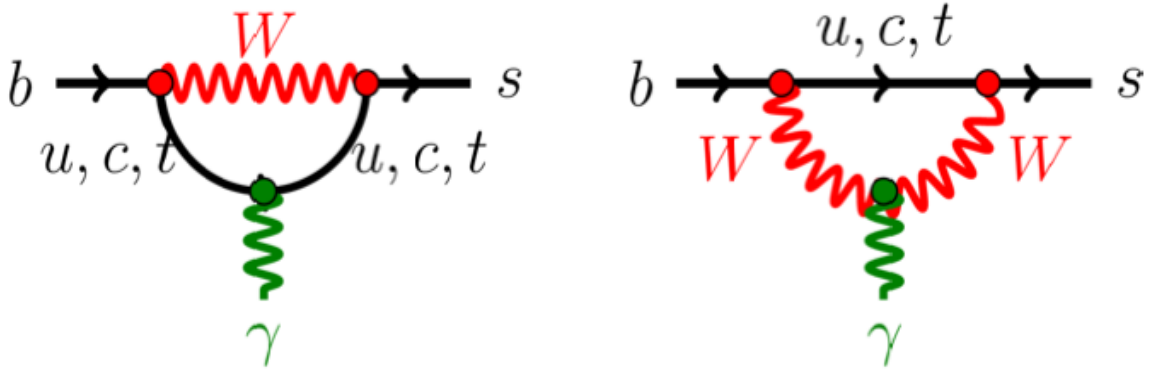
On behalf of the LHCb collaboration

# Outline

- Introduction
- Run1 achievements
  - BR & $A_{CP}$ in $B \to V\gamma$ modes
  - Photon polarisation
- Prospective
- Conclusion

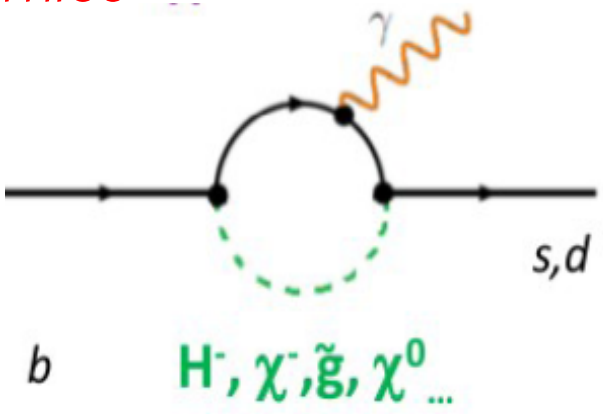
# Radiative b transitions

b→q $\gamma$ (q=d,s) transition : FCNC electro-magnetic penguin



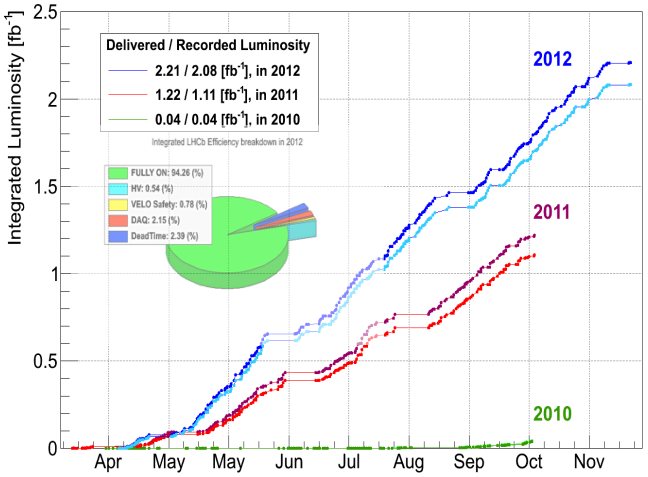

New physics affects the transition dynamics

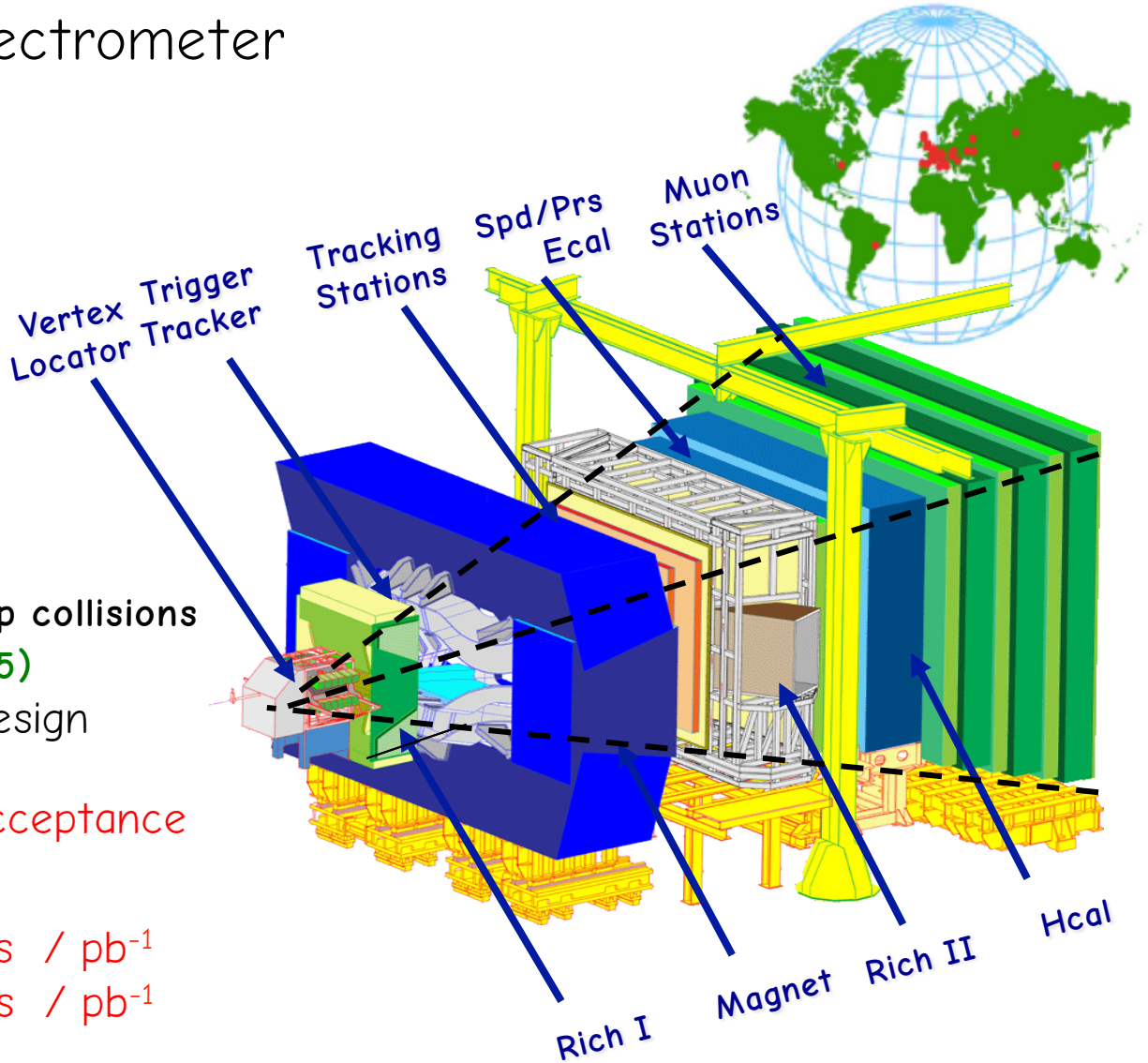
BR, $A_{CP}$, Isospin asymmetry,
helicity structure of the photon



# The LHCb experiment

## Single-arm forward spectrometer




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

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

factor 4 beyond the design

Integrated luminosity: **$3fb^{-1}$**

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

Radiative decay reconstruction rate

$B^0 \to K^{*0} \gamma$ : ~ 7 events / $pb^{-1}$

$B_s \to \phi\gamma$ : ~ 1 events / $pb^{-1}$

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

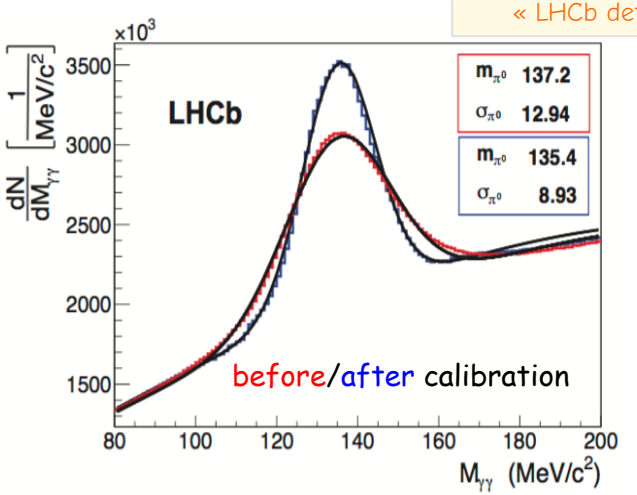
# Photon reconstruction @ LHCb

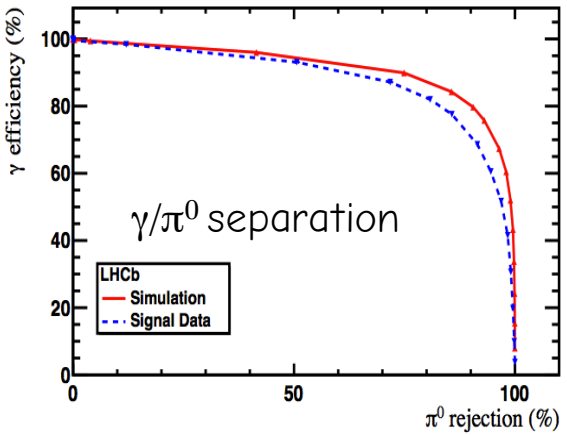
- Calorimetric photons: unconverted photons or conversion after magnet
  => from calorimeters deposit
- Di-electron photons: conversion before magnet
  => from tracking system

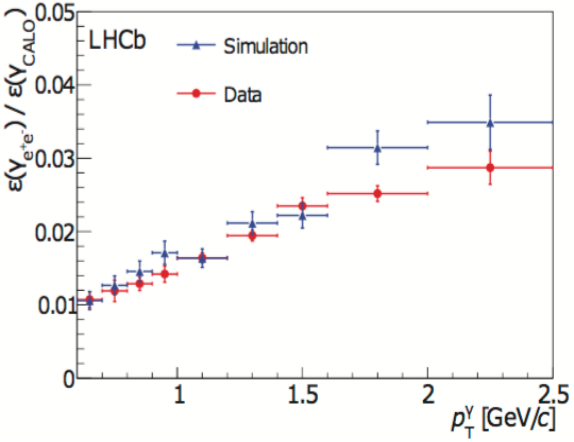
- Large calorimeter occupancy : large combinatorial background
  => neutralID to separate neutral EM showers from hadronic and electrons deposits

- Above $p_T$ ~2.5 GeV/c $\pi^0$ likely produced a single Ecal cluster
  ⇒ those $\pi^0$ represents an important background to high energy photons
  ⇒ $\gamma/\pi^0$ separation multivariate

« LHCb detector performances », IJMP A. Vol.30, No 7 (2015) 1530022



# Radiative decay anatomy

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

- L0 threshold in 2011(2012) : $E_T(\gamma) > 2.5\ (3.0)$ GeV
- Typical trigger efficiency on radiative modes ~ 30-40%
- For comparison : (di)muon channel $\varepsilon_{trg}$~80-90%

Mass resolution driven by calorimeter resolution :

$\sigma_M(B\to X\gamma) \sim 90$ MeV/c$^2$

For comparaison : $\sigma_M(B\to hh) \sim 25$ MeV/c$^2$

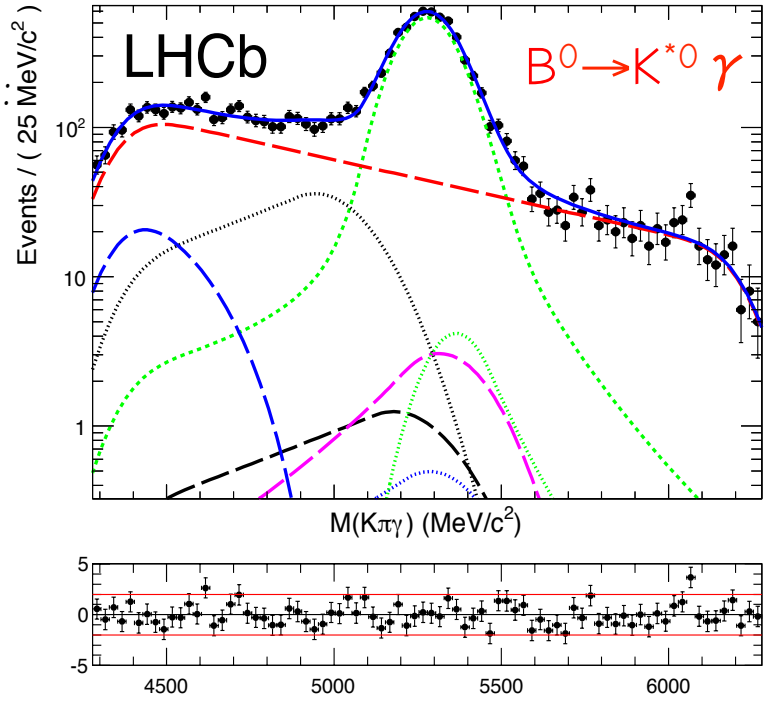
$\sigma_M(B\to J/\psi X) \leq 10$ MeV/c$^2$

No constraint on vertexing from $\gamma$ / 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 $b\to s\gamma$ decays
  - Partially reconstructed $b\to c$ $(X+hh\pi^0)$
- Specific peaking backgrounds :
  - Charmless $B_{d,s}\to h^+h^-\pi^0$
  - Irreducible $b\to d\gamma$ : $B_s\to K^{*0}\gamma$
  - b-baryons cross-feed $\Lambda_b\to\Lambda^*(K^-p)\gamma$

# Run 1 achievements

# $B \to V \gamma$ measurements

## $B_s \to \phi \gamma$ branching fraction

$BR(B^0 \to K^{*0}\gamma) = (4.33 \pm 0.15)\ 10^{-5}$ [Belle, Babar, Cleo]

$BR(B_s \to \phi\gamma) = (5.7^{+2.1}_{-1.8})\ 10^{-5}$ [Belle]

### SM-predictions

large hadronic uncertainty mostly canceling in the ratio :

[Ali, Pecjak, Greub, 2008]

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

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

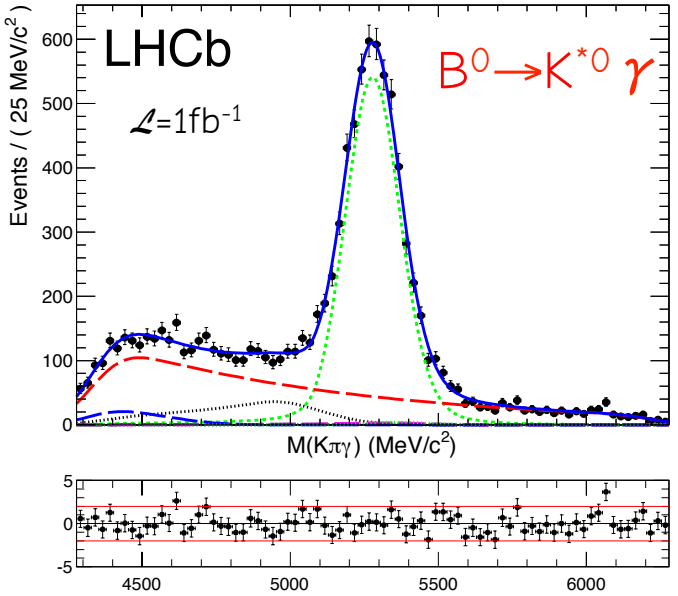
[Nuclear Physics B, 867, 1-18 (2013)]

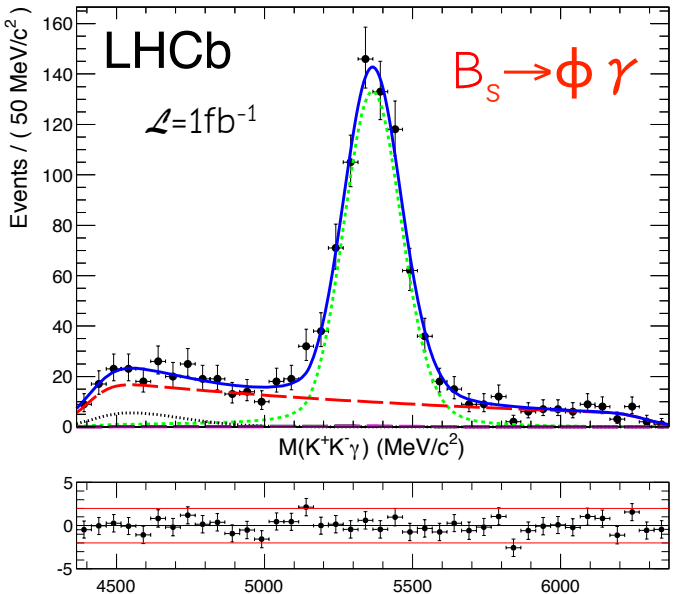
$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.23 \pm 0.06\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \pm 0.10\,(f_s/f_d)$$

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

### Main systematics

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



# $B \to V\gamma$ measurements

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

### 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

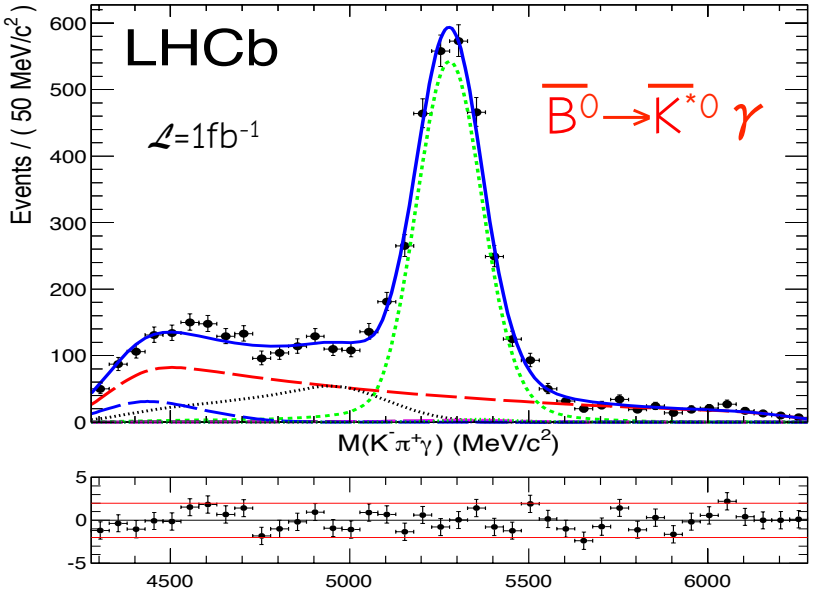
$$A_{CP} = -0.016 \pm 0.022 \pm 0.007$$

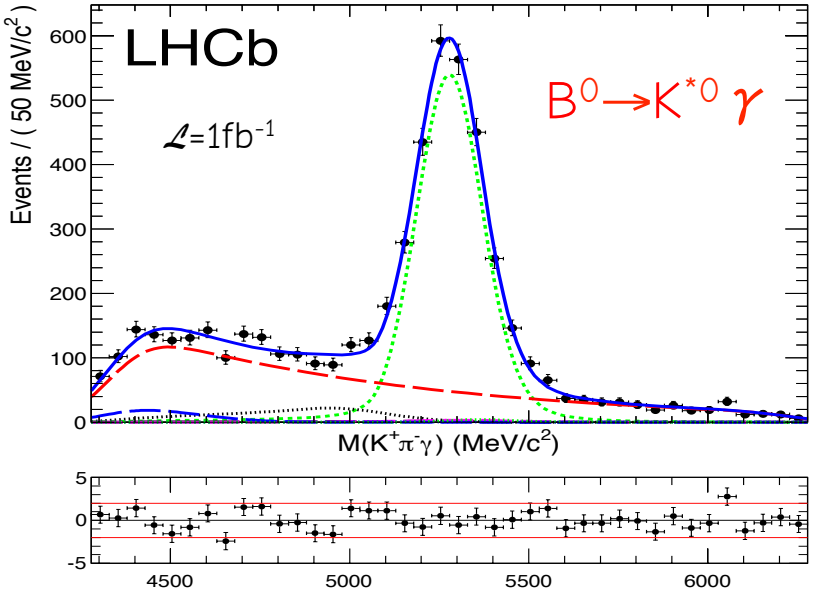
### LHCb result (1.0 fb$^{-1}$ - 2011 data) :

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

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

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



# B→V γ measurements

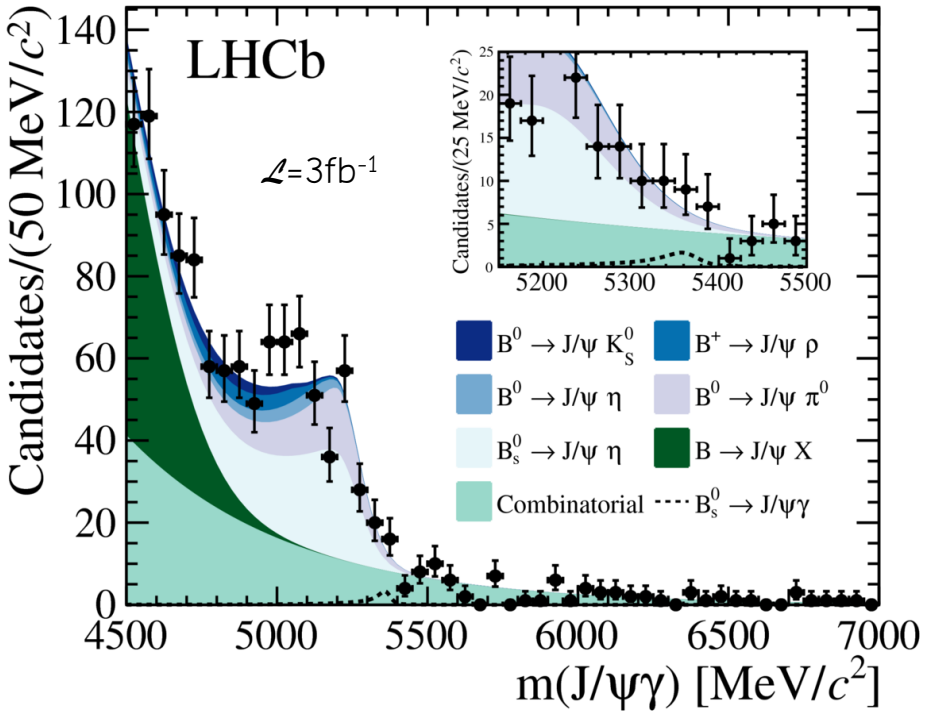
## Search for $B^0 \to J/\Psi\gamma$ & $B_s \to J/\Psi\gamma$

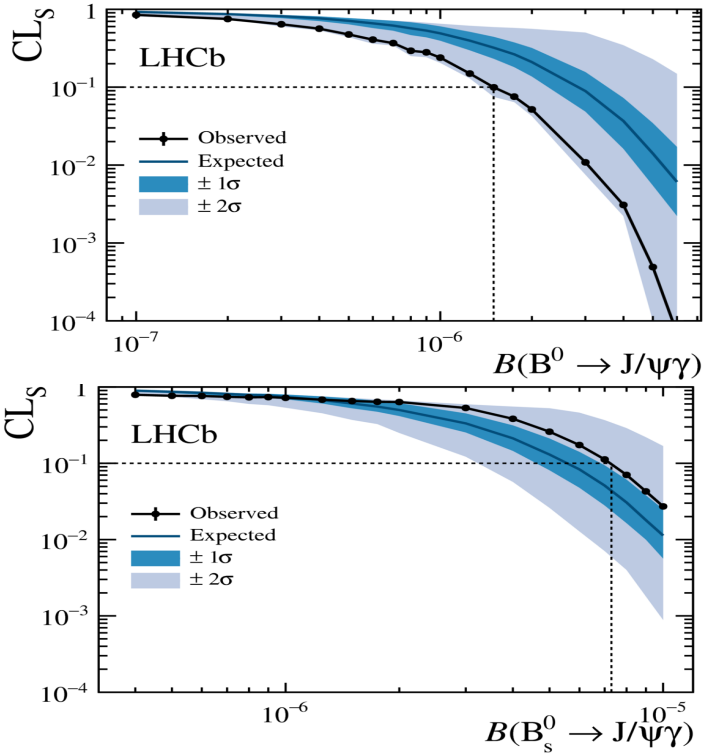
Not a radiative penguin transitions but share the same final-state problematics

PHYS. REV. D92 (2015) 112002

$BR(B^0 \to J/\Psi\gamma) < 1.7 \times 10^{-6}$
$BR(B_s \to J/\Psi\gamma) < 7.4 \times 10^{-6}$

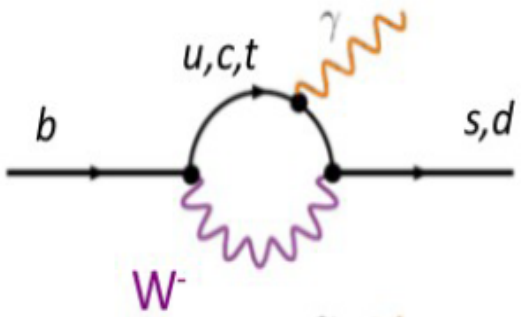
@ CL=90%



# Photon polarisation

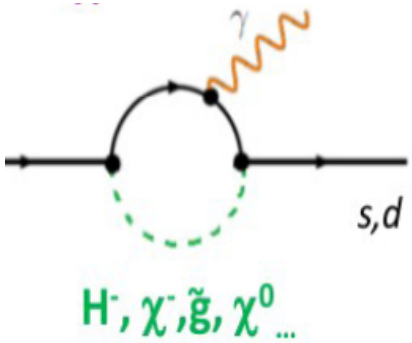
Due to the V-A structure of the electroweak interaction the photon is mostly left-handed in the radiative transition of the b-quark




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

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

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

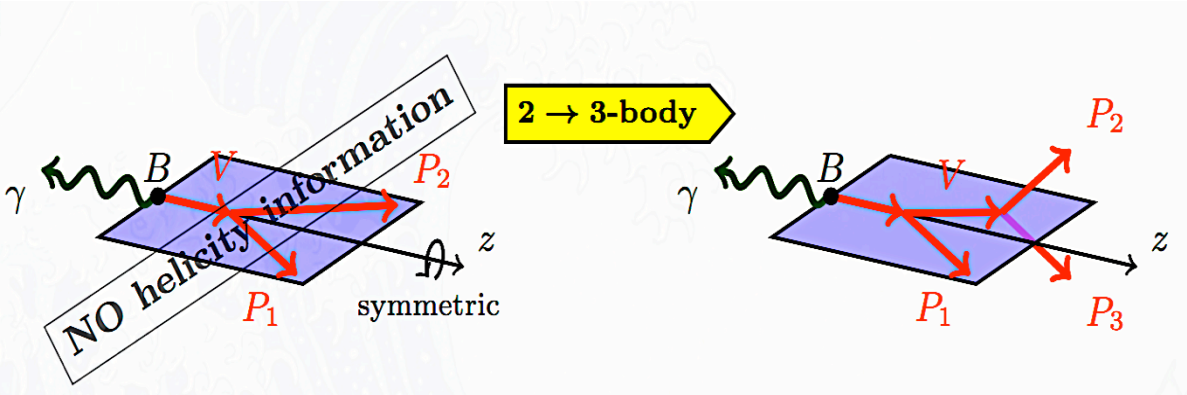



- Right-handed component could be enhanced in NP models

# Photon polarisation

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

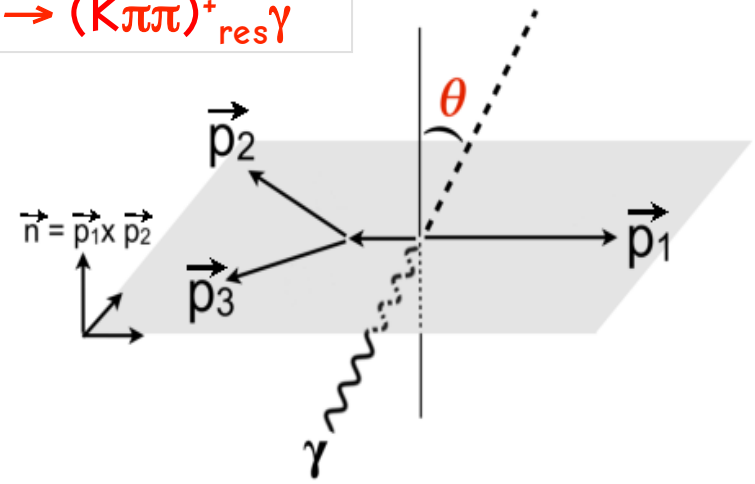
- angular analysis of the recoil 3-body in the $B \to \gamma + (hhh)_{res.}$ decay mode

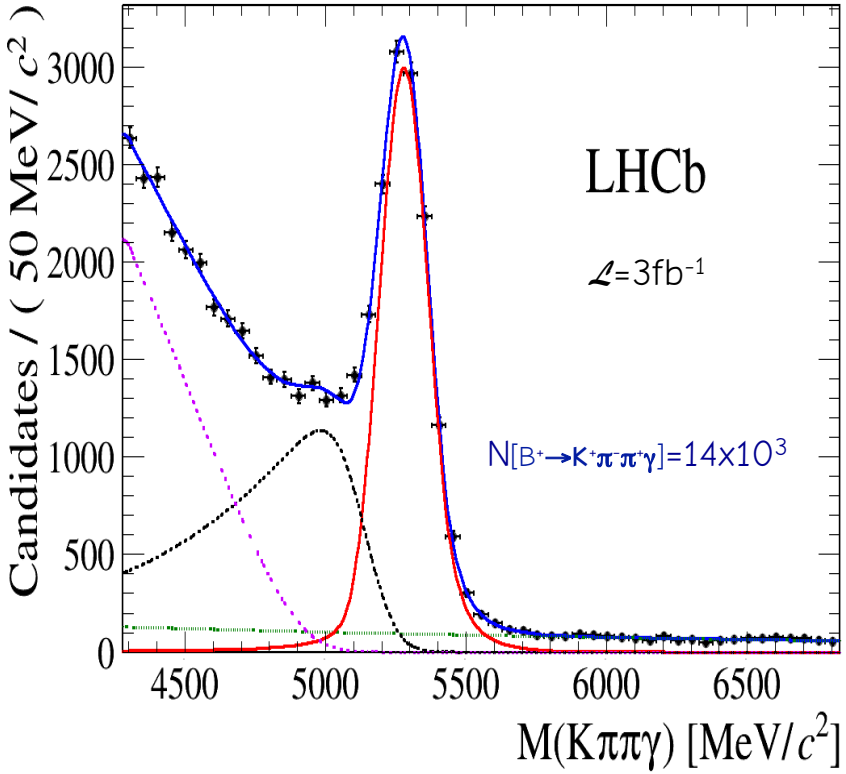



- time-dependent analysis of the $B \to \gamma + \Phi_{CP}$ decay modes
- di-lepton angular analysis at low $q^2$ of the (virtual) photon decay in $B \to V e^+ e^-$
- angular analysis in the radiative transition of b-baryons

# Helicity structure in $B \to (K\pi\pi)_{res}\gamma$

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



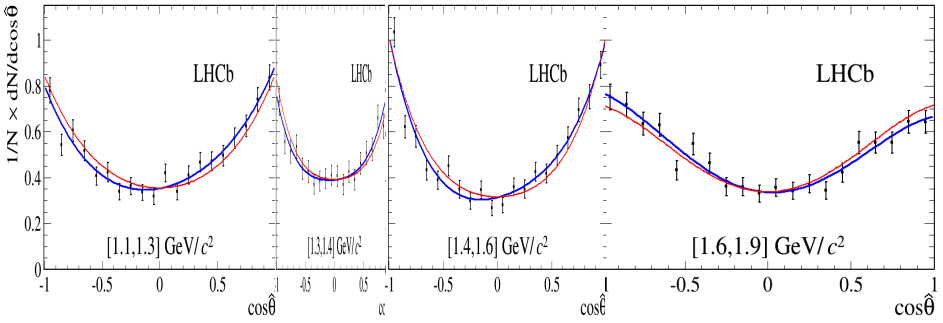

For a mixture of spin-parity $K_{res}(1^+,2^+,1^-)$ :

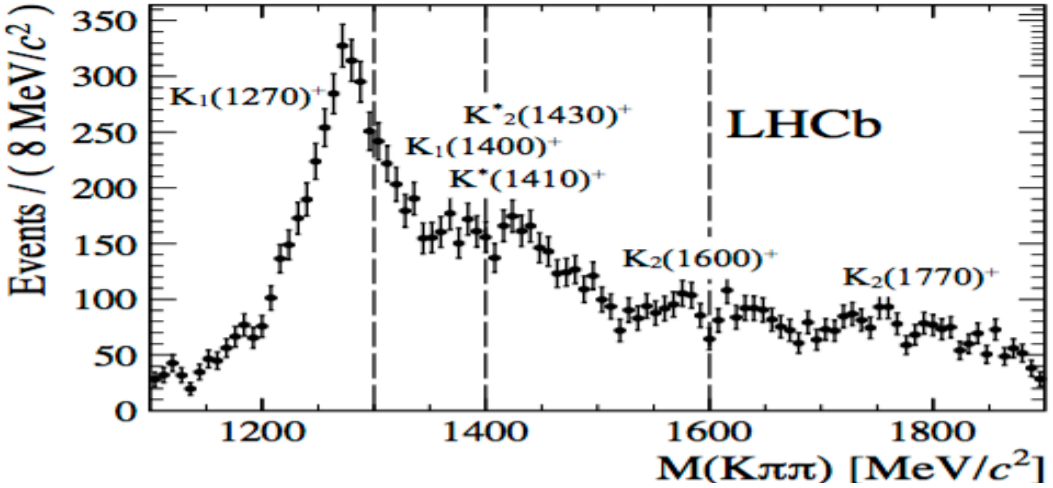
$$\frac{d\Gamma}{ds\, ds_{13}\, ds_{23}\, d\cos\theta} \propto \sum_{i=0,2,4} a_i(s, s_{13}, s_{23}) \cos^i\theta + \lambda_\gamma \sum_{j=1,3} a_j(s, s_{13}, s_{23}) \cos^j\theta$$

Up-down photon asymmetry is proportional to the photon polarisation $\lambda_\gamma$

Angular analysis of photon direction wrt to $(K\pi\pi)_{res}$ decay plane in different mass bins

# Helicity structure in $B \to (K\pi\pi)_{res}\gamma$




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

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

*First direct observation of photon polarization in b→sγ 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 $\lambda_\gamma$ value from the up-down asymmetry require to separate the (Kππ) resonances & theoretical determination of the helicity amplitude

e.g. for a single 1+ resonance

Phys. Rev. Lett. 88 (2002) 051802

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

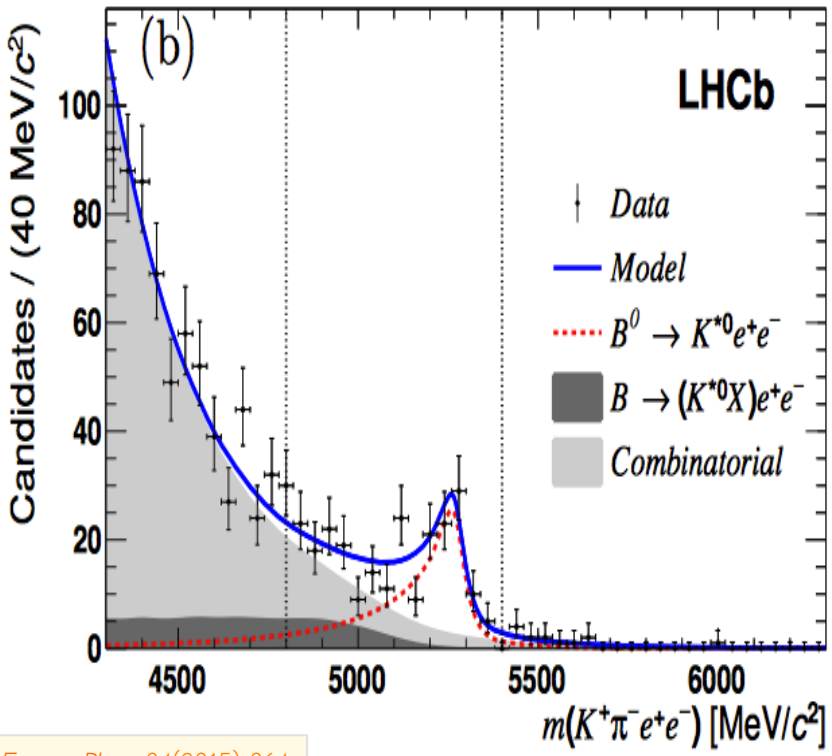
# Virtual photon : $B^0 \to K^{*0} e^+ e^-$

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

Branching fraction in [30 ; 1000] MeV/$c^2$
1.0 fb$^{-1}$ - 2011 data :

*J. High Energy Phys.* 05 (2013) 159

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




Full angular analysis in [20; 1120]MeV/$c^2$
3.0 fb$^{-1}$ – 2011+2012 data :

*J. High Energy Phys.* 04(2015) 064

$$F_{\mathrm{L}} = 0.16 \pm 0.06 \pm 0.03$$
$$A_{\mathrm{T}}^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_{\mathrm{T}}^{\mathrm{Im}} = +0.14 \pm 0.22 \pm 0.05$$
$$A_{\mathrm{T}}^{\mathrm{Re}} = +0.10 \pm 0.18 \pm 0.05,$$

Related to the photon polarisation

# Time-dependent decay rate

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

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

*untagged* / *tagged analysis required*

$$\mathcal{S}_{CP} \sim \sin 2\psi \sin\phi_{(s)} \qquad \mathcal{A}_\Delta \sim \sin 2\psi \cos\phi_{(s)} \qquad \tan\psi = \left|\frac{\mathcal{A}_R}{\mathcal{A}_L}\right| \qquad \phi_{(s)} : B^0_{(s)} \text{ mixing phase}$$

- $B^0$ decays : access to the polarisation through the TD asymmetry term $\mathbf{S_{CP}}$
  Out of LHCb reach for the main decay mode $B^0 \to K_s\pi^0\gamma$

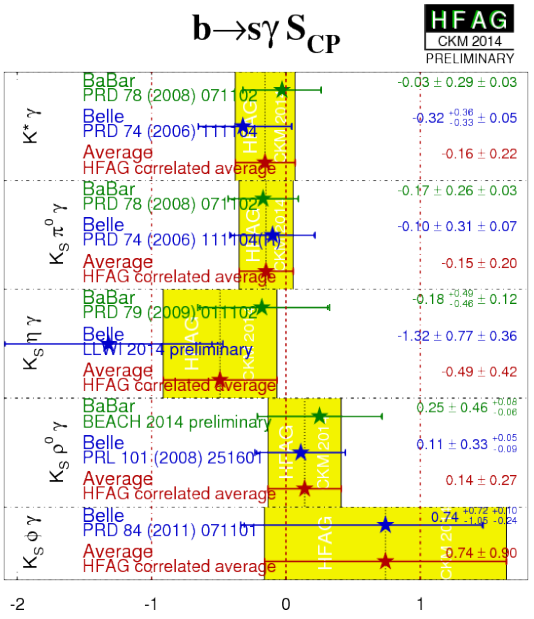
- $B_s$ decays : access through the mixing term $\mathbf{A_\Delta}$

*Muheim et al., PLB664(08)17*

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

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

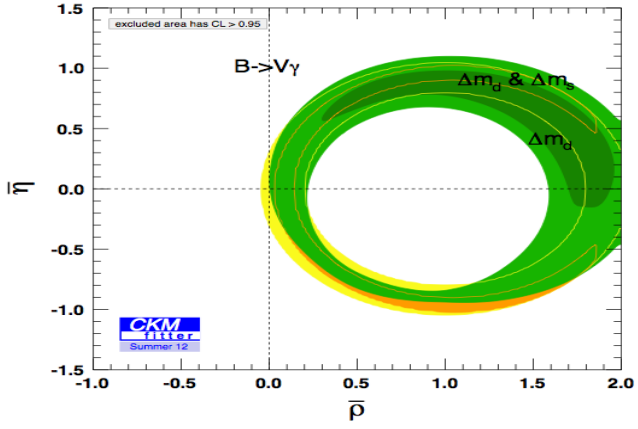
LHCb : ongoing untagged analysis of the $B_s \to \phi\gamma$ decay rate
Expected statistical resolution : $\sigma_{A^\Delta} \sim 0.4$
Measurement statistically limited ( $3\times10^3$ rec'ed $B_s$)



# Prospective

# Prospective

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




- e.g $V_{td}$ suppressed b→dγ penguin

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

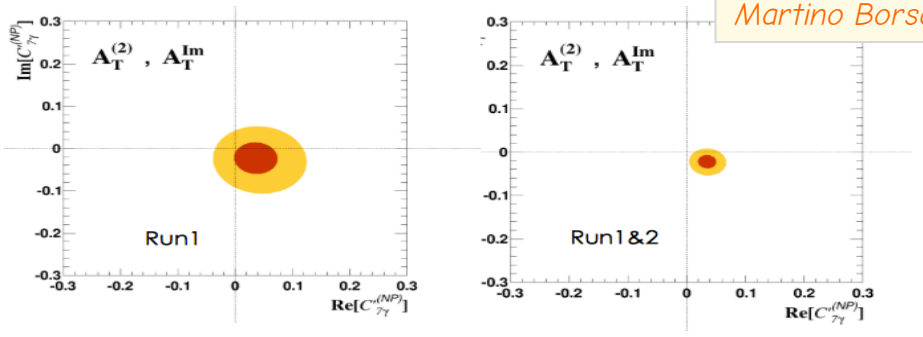
Such transition could be accessible in LHCb via $B^0 \to \rho^0/\omega\,\gamma$ , $B^+ \to a_1^+\gamma$

Could separate the b→dγ transition $B_s \to K^*\gamma$ from b→sγ in $B^0$ using converted photons

- Photon polarisation : reach < 10 % resolution

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

*Martino Borsato*




Prospective from K*ee angular analysis

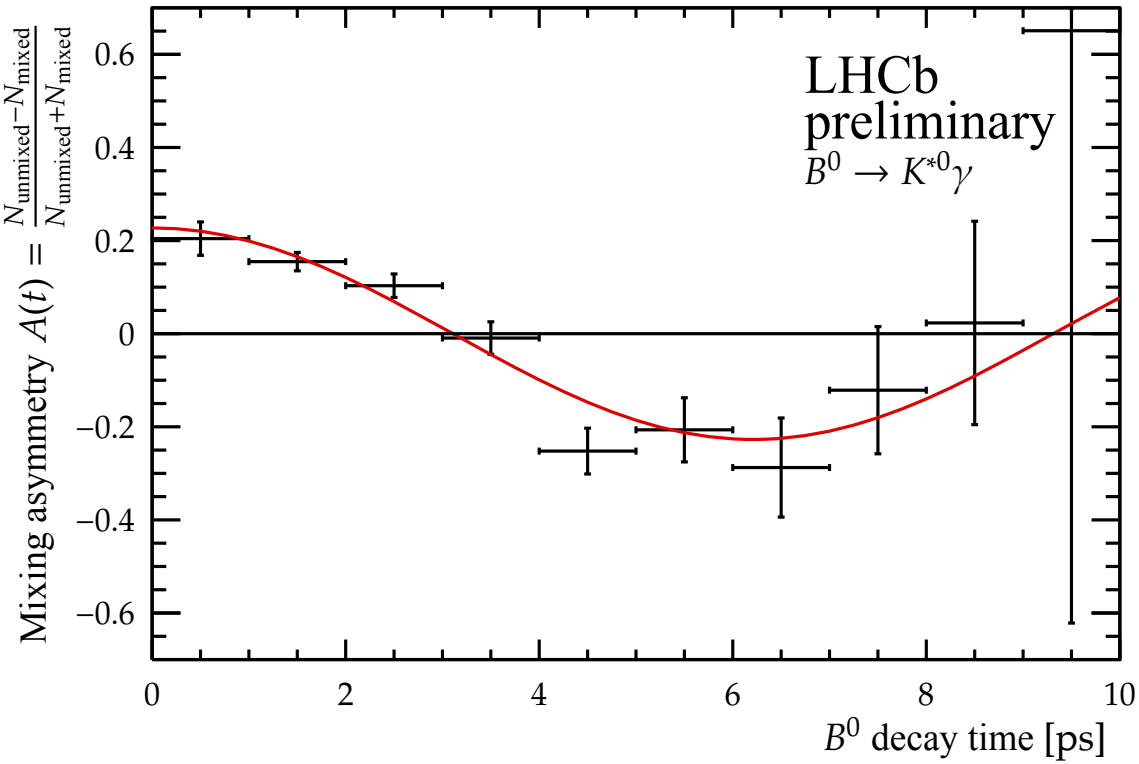
# Prospective

- Photon polarisation (cont')

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

For illustration :

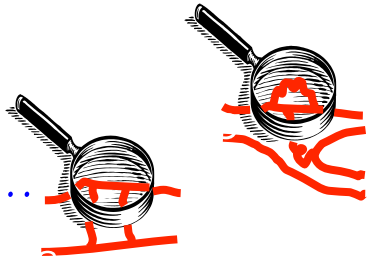
LHCb tagging performance applied for the first time on a radiative decay



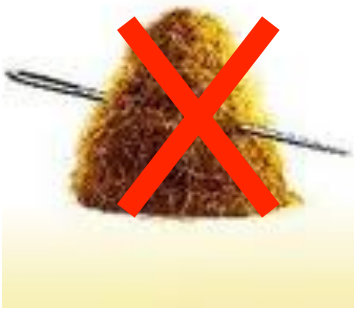
# Conclusions

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 expected soon
run 2 will allow to explore rarest radiative decays

# Spare

# $B_s \to \phi\gamma$ Branching Fraction

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

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

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

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

- Background model (±2%)

  Contamination level and shape

- Reconstruction and selection (±2%)

  Trigger and selection efficiencies, Particle reconstruction & identification

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

both statistical and systematical uncertainty will improve

(more precise fs/fd, improved background model ...)

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

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

  *From charm $D^0 \to K\pi$ 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 $B \to J/\psi K^*$ 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 $\Lambda_b \to (pK)\gamma$ contamination*

- Detector non-uniformity $\Delta A_{CP} = (+0.1 \pm 0.2)\%$

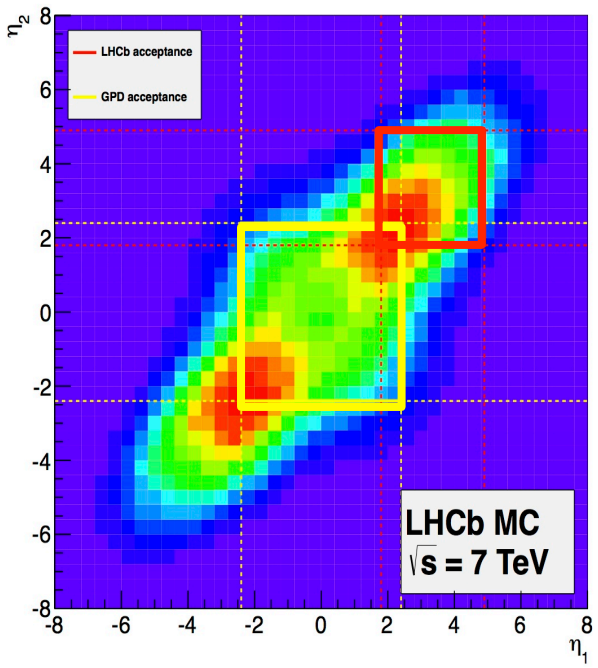
  *Possible detector bias strongly reduced by switching regularly the magnet polarity*

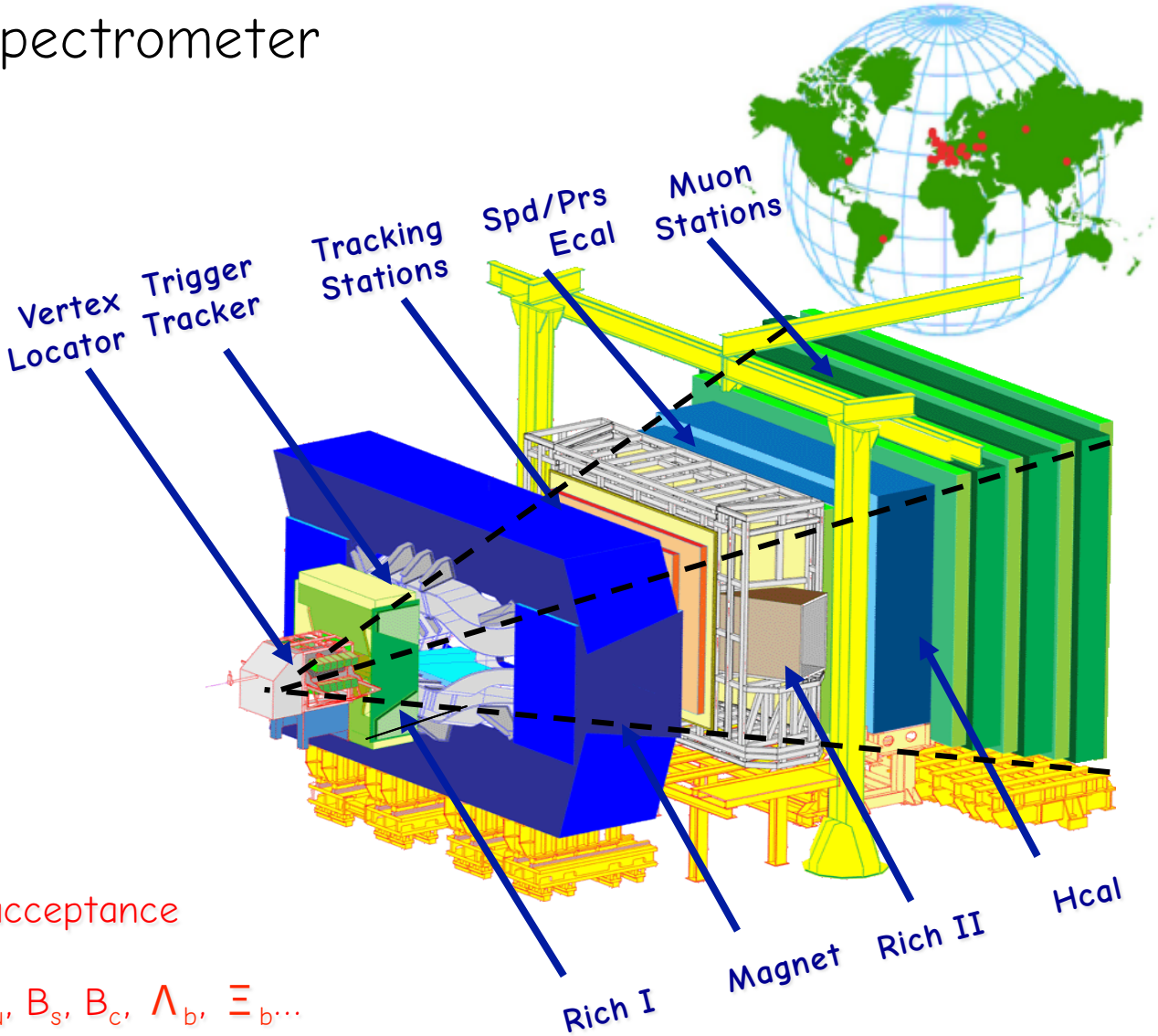
Update with whole $3fb^{-1}$ sample ongoing

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

# The LHCb experiment

## Single-arm forward spectrometer



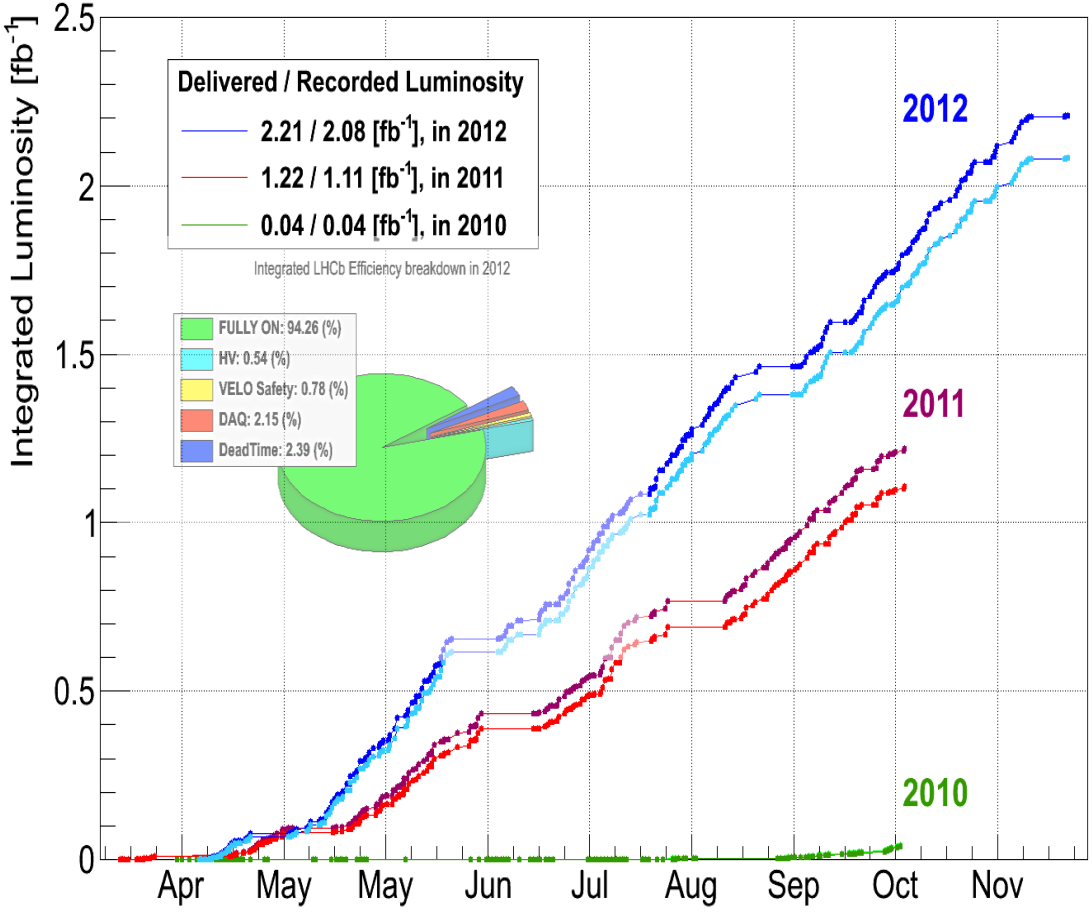

Large bb rate in the detector acceptance

Access to all b species : $B_d$, $B_u$, $B_s$, $B_c$, $\Lambda_b$, $\Xi_b$...

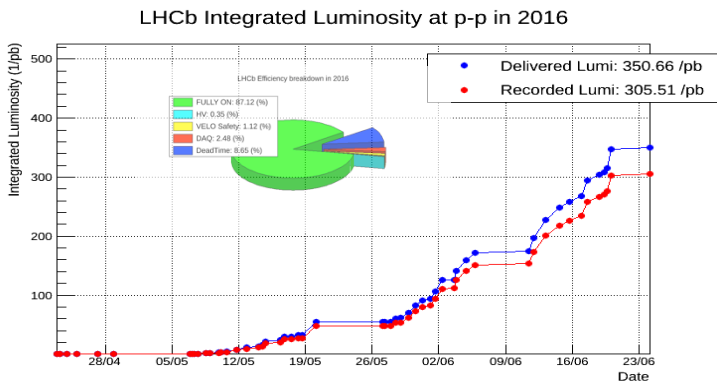
# LHCb operations

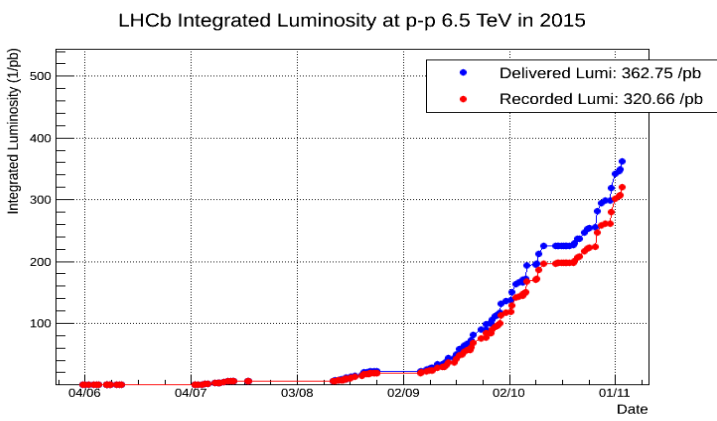
- **RUN 1 (2010-2013) : $\sqrt{s}$=7 TeV and $\sqrt{s}$=8 TeV pp collisions**

| | | |
|---|---|---|
| Instantaneous luminosity | : $4 \times 10^{32}$ cm$^{-2}$s$^{-1}$ | factor 2 beyond the design |
| Visible pp interaction/crossing | : O(1.5) | factor 4 beyond the design |
| Integrated luminosity | : 3fb$^{-1}$ | ~2 x$10^{11}$ bb in LHCb acceptance |




- **RUN 2 (2015-2018) $\sqrt{s}$=13 TeV**



# 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 $b\to s\gamma$ transition of neutral b-hadrons : $B^0$,$B_s$, $\Lambda_b$
  - $(h^+h^-h^+)\gamma$ channel from charged b-hadrons
  - Same for suppressed $b\to d\gamma$ transitions when accumulating statistics

- What LHCb could probably do :
  - $(h^+h^-\pi^0)\gamma$ , $(h^+h^-K_s)\gamma$ : e.g $K_1{}^0\gamma$ maybe $B\to\omega\gamma$
  - $B^+\to K^{*+}(K_s\pi^+)\gamma$ : e.g isospin asymmetry in $K^*\gamma$
  - $\Lambda_b\to\Lambda_{1115}\gamma$ : very challenging

- What LHCb can't do
  - $B^+\to K^{*+}(K^+\pi^0)\gamma$ and a fortiori $B^+\to\rho^+(\pi^+\pi^0)\gamma$
  - $B^0\to K^{*0}(K_s\pi^0)\gamma$ : time-dependent asymmetry in radiative Bd
  - inclusive $b\to X_s\gamma$ BR