Radiative B decays at LHCb

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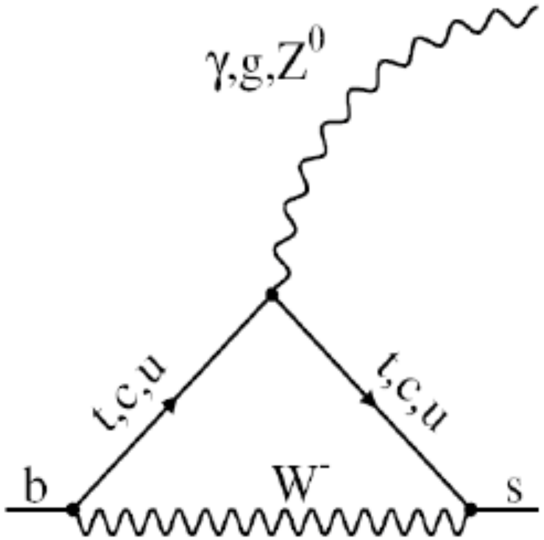
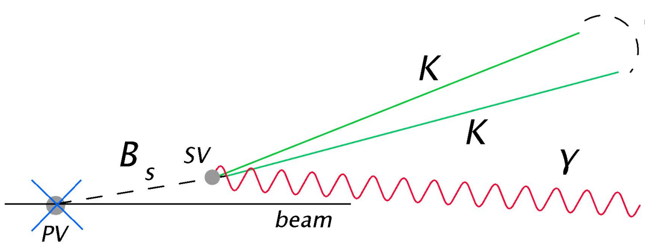
Radiative decays: theory

Radiative decays are FCNC processes:

- Not allowed at tree level
- New Physics (NP) may introduce sizeable effects on the dynamics of the transitions, through contributions of new particles inside the loops
- Observables: Branching Ratios, photon polarization and asymmetries (isospin, CP)



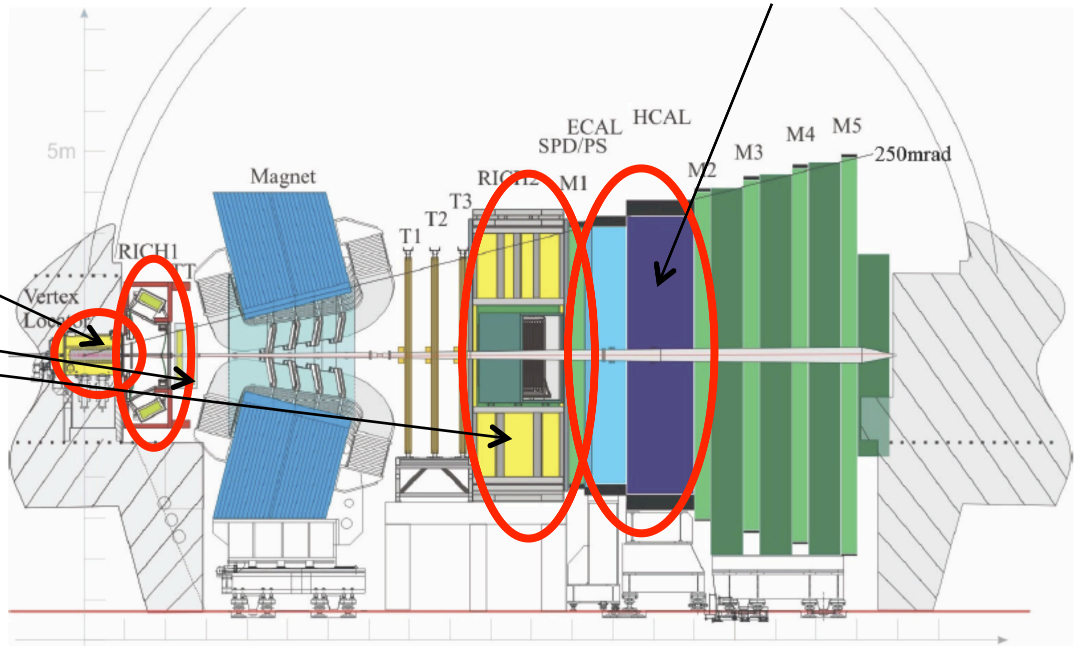
LHCb



Velo: Excellent vertex resolution

RICH: excellent π/K separation within 2-100 GeV

Calorimeters: Particle identification and neutral particles energy measurement



Data collected:

- 2011: $1fb^{-1}$
- 2012: $2fb^{-1}$

Results today: Mostly $1fb^{-1}$ except one analysis, using $2fb^{-1}$

Published work

Branching Ratios

Analysis performed for the radiative B decays with larger BR, $B \to K^*(\to K^+\pi^-)\gamma$ and $B_s \to \phi(\to K^+K^-)\gamma$

SM predictions:

- $BR(B_s \to \phi\gamma) = (4.3 \pm 1.4)10^{-5}$ [*Phys. Rev. D, 75 (2007)*]
- $R \equiv \dfrac{BR(B_d \to K^*\gamma)}{BR(B_s \to \phi\gamma)} = 1.0 \pm 0.2$ [*Eur. Phys. J. C55 (2008) 577*]

Already measured at the B-factories, with low precision:

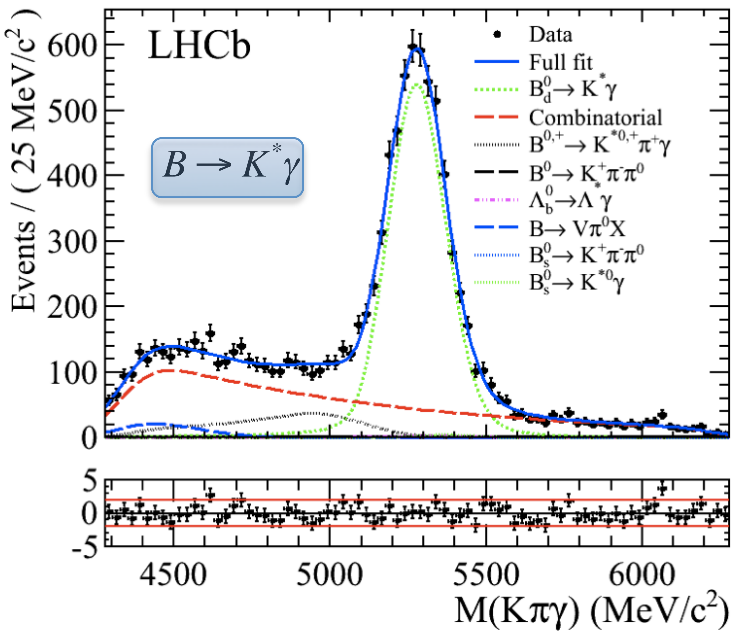
- $BR(B \to K^*\gamma) = (44.7 \pm 1.0 \pm 1.6)10^{-6}$ by BaBar [*Phys.Rev.Lett. 103 (2009) 211802)*]
- $BR(B_s \to \phi\gamma) = (57^{+18+12}_{-15-11})10^{-6}$ by Belle [*Phys.Rev.Lett. 100 (2008) 121801*]
- Both in agreement with the SM
- Large room for improvement in the $B_s \to \phi\gamma$ channel

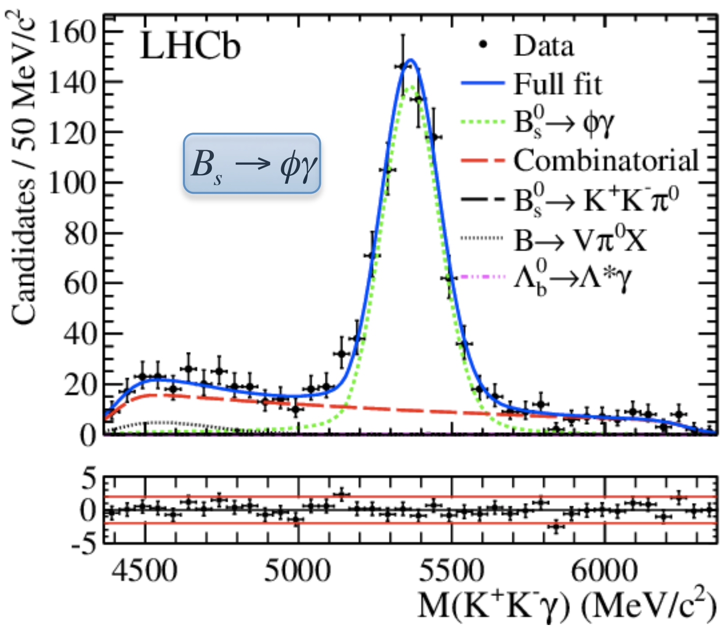
Branching Ratios

The measurement of the ratio of Branching Ratios leads to the cancellation of systematic uncertainties

$$N = L\sigma_{b\bar{b}}\, 2 f_i\, BR(channel)\,\varepsilon \;\rightarrow\; R = \frac{BR(B^0 \to K^{*0}\gamma)}{BR(B_s \to \phi\gamma)} = \frac{N_{sig}^{B^0\to K^{*0}\gamma}}{N_{sig}^{B_s\to\phi\gamma}} \frac{BR(\phi \to K^+K^-)}{BR(K^* \to K^+\pi^-)} \frac{f_s}{f_d} \frac{\varepsilon_{B_s\to\phi\gamma}}{\varepsilon_{B^0\to K^*\gamma}}$$

- PDG (green)
- LHCb measurement [arXiv:hep-ex/1111.2357] (purple)
- From fitting the data (blue)
- From data and simulation (red)





$1fb^{-1}$ used

Branching Ratios Results

Best (most precise) world measurement:

- $R = \frac{BR(B_d \to K^* \gamma)}{BR(B_s \to \phi\gamma)} = 1.23 \pm 0.06(stat) \pm 0.04(syst) \pm 0.10(f_d / f_s)$

Extracting the BR value for $K^*\gamma$ from the PDG $BR(B \to K^* \gamma) = (4.33 \pm 0.15)10^{-5}$, we find:

- $BR(B_s \to \phi\gamma) = (3.5 \pm 0.4)10^{-5}$

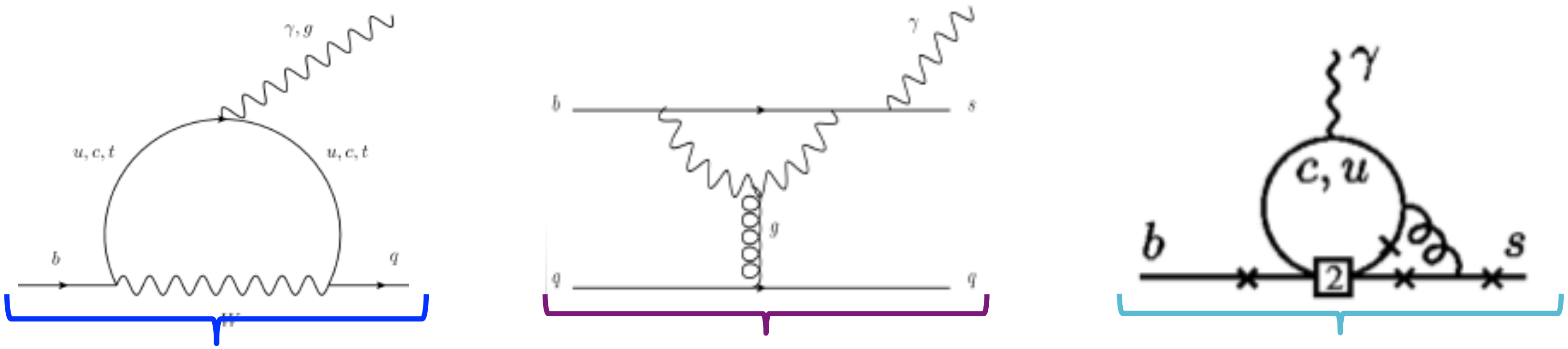
[*Nucl. Phys. B 867 (2012) 1-18*]

CP Asymmetry

CPV arises when there is more than one diagram (with a phase change) to connect an initial and a final state

- The different paths interfere, yielding to differences in the amplitude of the transition when doing the CP conjugate

Within the SM, the $B \rightarrow K^{*}\gamma$ channel is dominated by the electromagnetic penguin decay ($C_{7\gamma}$) with little interference from the chromomagnetic operator (C_{8g}) [*Phys. Rev. D72 (2005) 014013*] although NP models predict enhancements through other diagrams [*Phys. Rev. D58 (1998) 094012*]



The SM prediction is: $\mathbf{A_{CP} = (-0.61 \pm 0.43)\ \%}$

CP Asymmetry

The direct CP asymmetry for the $B \to K^* \gamma$ channel is defined as:

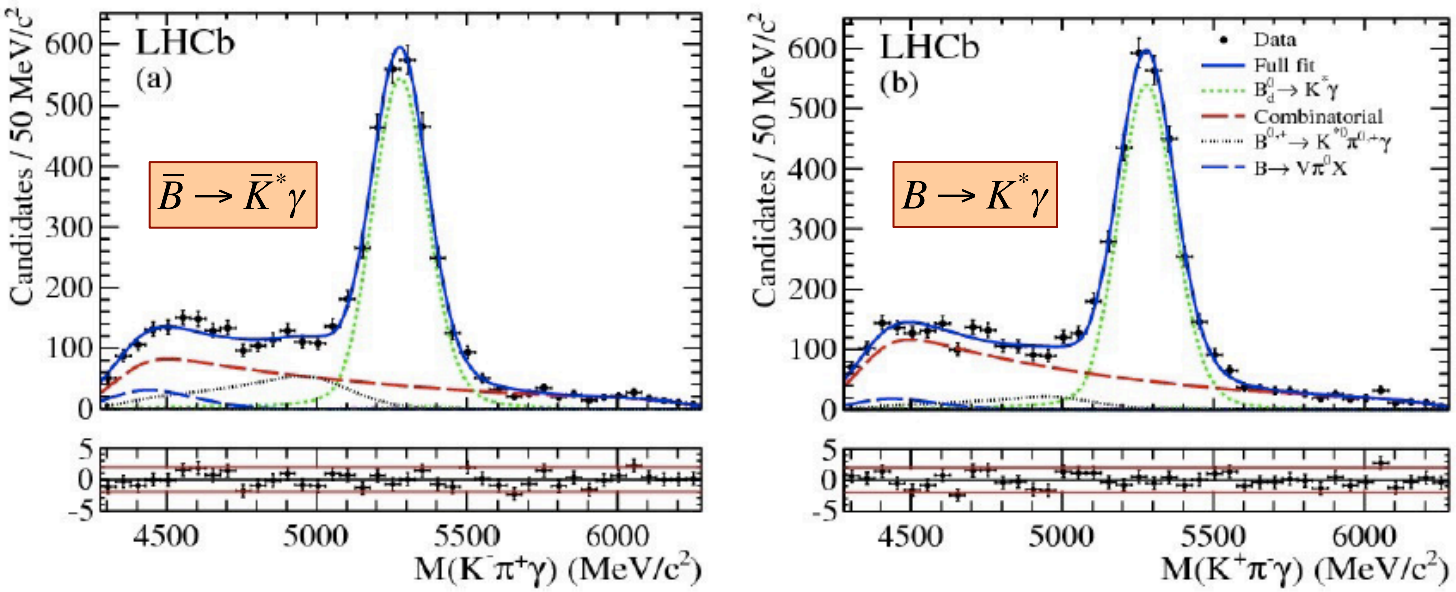
$$A_{CP}^{raw} = \frac{N(\bar{B}^0 \to \bar{K}^{*0}\gamma) - N(B^0 \to K^{*0}\gamma)}{N(\bar{B}^0 \to \bar{K}^{*0}\gamma) + N(B^0 \to K^{*0}\gamma)}$$

where $K^* \to K^+\pi^-$ and $\bar{K}^* \to K^-\pi^+$

The charge of the kaon/pion identifies the flavour of the K* meson

It was already measured by Belle with very large uncertainties:

$$A_{CP}(B \to K^*\gamma) = (-2.2 \pm 4.8 \pm 1.7)\%$$ [*Phys. Rev. D 69, 112001 (2004)*]



1fb^{-1} used

CP Asymmetry

Measurement of the raw A_{CP} asymmetry needs to be corrected:

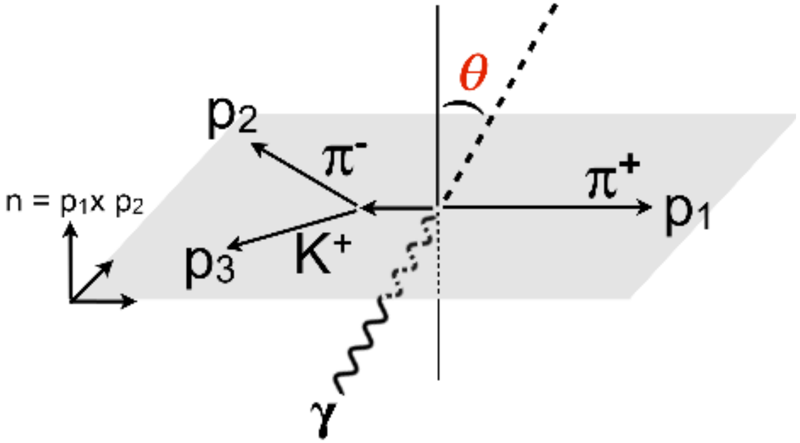
- Detection asymmetry (A_D):
  - Different particle/antiparticle interaction with the detector, measured using $B_{(s)} \to K^+\pi^-$ decays [*Phys Rev Lett 108 (2012) 201601*]
  - Magnet effect: minimised by changing the polarity
- Production asymmetry (A_P): The LHC is a *pp* machine, leading to production asymmetry of B^0 mesons, measured with the B^0 meson production ratios [*Phys Rev Lett 108 (2012) 201601*]
- Dilution factor (κ): due to neutral B meson mixing

$$A_{CP}(B \to K^*\gamma) = (0.8 \pm 1.7(stat) \pm 0.9(syst))\%$$

[*Nuclear Physics, Section B 867 (2013)*]

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

Three-body + photon decays allow the study of photon polarization through the daughters of the kaon resonance



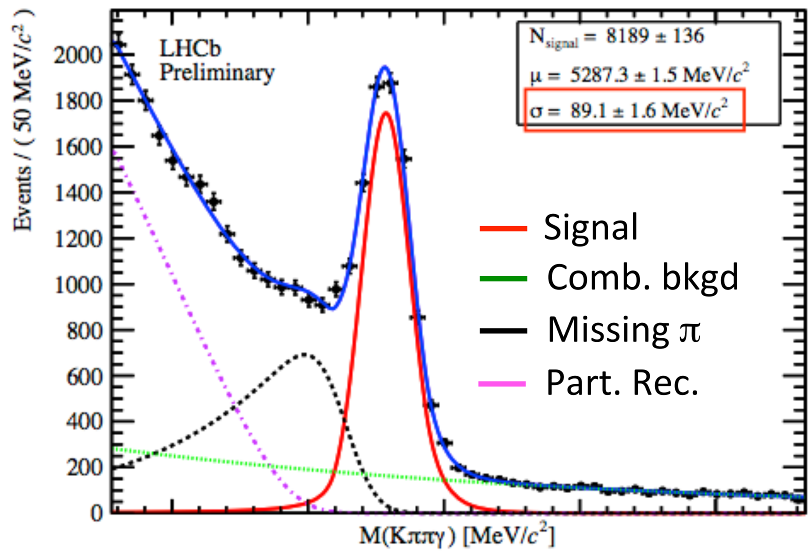
The non-zero polarization of the photon determines the angular distribution of the final state particles

2fb^{-1} used

Too little theoretical knowledge prevents a value for the polarization: only significance with respect to no-polarization can be extracted

$$A_{UD} = -0.085 \pm 0.019(stat) \pm 0.003(syst)$$

First observation of photon polarization in radiative decays with a 4.6 σ significance



[*LHCb-CONF-2013-009*]

Outlook

Multichannel analysis

Several channels to be analysed simultaneously:

- $B^0 \to K^*(K\pi)\gamma$
- $B_s \to \phi(KK)\gamma$

Studied on their own for 1fb^{-1}, update to 3fb^{-1} within this analysis

- $B^0 \to \rho(\pi\pi)\gamma$: $BR(B \to \rho\gamma) = (4.9 \pm 1.8)10^{-7}$
- $\Lambda_b \to \Lambda^*(Kp)\gamma$: never observed

They all have very similar topologies: the *b*-hadron flies about the same distance, the intermediate resonance does not fly, a high E_T photon and two tracks in the final state

Many observables to measure:

- Branching fractions of each of the channels
- CP asymmetry for two of the channels: $B^0 \to K^*(K\pi)\gamma$ and $\Lambda_b \to \Lambda^*(Kp)\gamma$

Multichannel analysis

Take advantage of common parameters in the fit:

- Yields from one channel into the others
- B^0 mass forced to be the same in the two channels where it is involved

Use $B^0 \rightarrow K^*(K\pi)\gamma$ as control channel

Correct particle identification is vital for this analysis

- New analysis now include information from the tracking system
- Neural net developed to take into account correlation between PID variables

Preliminary studies show improvement on the PID. Examples:

- Factor 1.2 improvement in kaon efficiency for the same pion misID rate
- Factor 6 improvement in proton rejection for the same pion efficiency

Expect more than statistical improvement

Other analysis for the future

- $B \to VP\gamma$
- $b \to d\gamma$
- Photon polarization: See Pablo's talk

$B \to VP\gamma$

Three channels under study:

- $B^+ \to \phi K^+ \gamma$
- $B^+ \to K^* \pi^+ \gamma$
- $B^+ \to K_1(1270)^+ \gamma$

The SM predicts A_{CP} of the order O(%)

- The only measurement is from BaBar for the $B^+ \to \phi K^+ \gamma$ channel: A_{CP} = (-26±15)% [*Physical Review D 75 (2007) 051102*]

Belle measured the $B^+ \to K_1(1270)^+ \gamma$ BR:

- $BR(B^+ \to K_1(1270)^+ \gamma) = (4.3 \pm 0.9 \pm 0.9)10^{-5}$ [*Phys. Rev. Lett. 94, 111802 (2005)*]
- Large uncertainties

Useful for photon polarization studies

Very preliminary but promising results at LHCb

$b \to d\gamma$

The SM predicts an A_{CP} of 10% in the charged modes

These decays give access to $|V_{td}|/|V_{ts}|$ using $B \to \omega\gamma$ and $B \to \rho\gamma$ vs. $B \to K^{*}\gamma$

Very low Branching Ratio:

- Theory: $BR(B \to \rho\gamma) = (4.9 \pm 1.8)10^{-7}$ [*arXiv:hep-ex/0209346*]
- Experimental: $BR(B \to \rho\gamma) = (8.6 \pm 1.5)10^{-7}$ [*PDG average*]

Difficult to access experimentally:

- Very low Branching Ratio
- The final state allows much contamination from combinatorial background
- For the charged modes there is a neutral π^0 in the final state
- The ρ meson natural width is large

Conclusions

- Radiative B decays are sensitive probes to NP
- The first LHCb results have largely improved the previous measurements:
  - $R = \frac{BR(B_d \to K^* \gamma)}{BR(B_s \to \phi\gamma)} = 1.23 \pm 0.06(stat) \pm 0.04(syst) \pm 0.10(f_d / f_s)$
  - $BR(B_s \to \phi\gamma) = (3.5 \pm 0.4)10^{-5}$
  - $A_{CP}(B \to K^* \gamma) = (0.8 \pm 1.7(stat) \pm 0.9(syst))\%$
  - First evidence of photon polarization in radiative B decays
- Many interesting analyses underway

Back-up

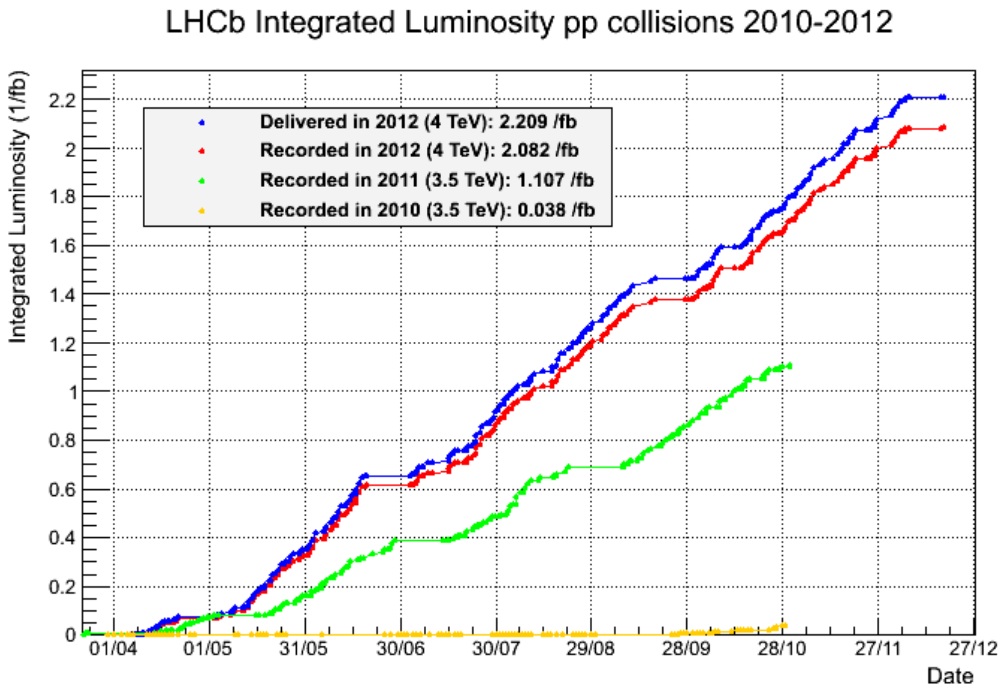
Radiative trigger:
L0 radiative dedicated trigger line:

- High photon transverse momentum

Correction to photon polarization in radiative B decays:

- Up to 10%

LHCb performance



$3fb^{-1}$ on tape (2010+2011+2012)

$3fb^{-1}$/year in 2015-2018

$5fb^{-1}$/year after upgrade

B+ to K pi pi gamma

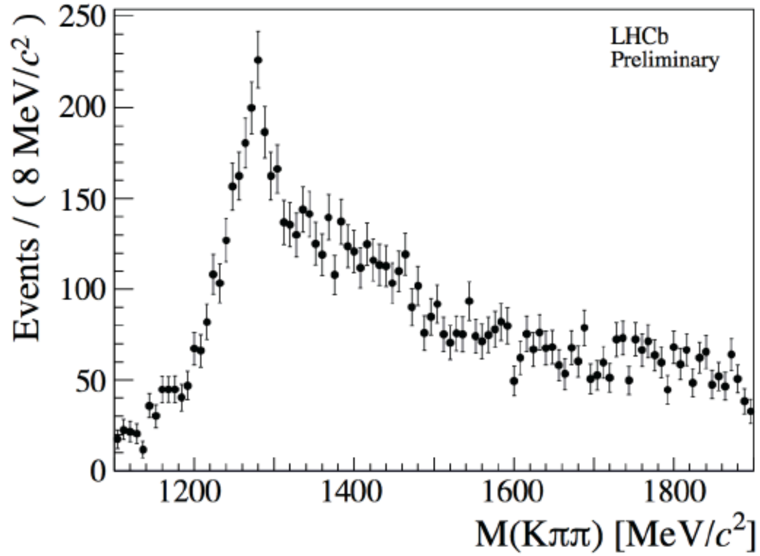


Figure 3: Background-subtracted $K^+\pi^-\pi^+$ invariant mass distribution, obtained using the *sPlot* technique [24].

All the resonances contaminate each other:

- Can't separate them
- Need to do an inclusive analysis

Also measured A_{CP}:

- A_{CP} = -0.007 +- 0.015(stat) +-0.008(syst)

Photon polarization for $B_s \to \phi\gamma$

The SM predicts the photon from $b \to s\gamma$ to be left-handed polarized up to $O(m_s/m_b)$ but it has never been tested to high precision ➔ A deviation from the SM prediction would imply the presence of New Physics

$$\Gamma(B_q \to f^{CP}\gamma) = |A|^2 e^{-\Gamma_q \tau}[\cosh(\Delta\Gamma_q \tau/2) + A_q^{\Delta}\sinh(\Delta\Gamma_q \tau/2) \pm C_q \cos(\Delta m_q \tau) \mp S_q \sin(\Delta m_q \tau)]$$

Places to measure the photon polarization

- The A^{Δ} term is independent of the quark content of the mesons, is not sensitive to the proper time resolution but needs to control the proper time acceptance function

- The Δm term requires flavour-tagging and is limited by the proper time resolution

Two approaches for this analysis:

- **IFIC**: Use of the well known channel $B \to K^*\gamma$ to control the bias induced by the acceptance function. Studying the ratio of acceptances and how one selection affects the other. A ratio close to a flat distribution, a fit to A^{Δ} can be performed
- **Université de Clermont-Ferrand**: Use of $B_s \to \phi J/\psi$ as control channel to avoid uncertainties induced by the poor knowledge of the photon properties. A similar study for $B \to K^*\gamma$ and $B \to K^* J/\psi$ to validate the method

[See Pablo's talk]

Isospin asymmetry

For the well-known $B \to K^* \gamma$ channel, the isospin asymmetry is defined as:

$$A_I = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}$$

It is very sensitive to NP effects:

- New physics in the C_7-$C_{7'}$ plane [*hep-ph/1104.3342*]
- Constrains on MSSM and mSUGRA

Already measured at CLEO but with very large uncertainties [*Phys.Rev.Lett. 103 (2009) 211802*]:

- $0.017 < A_I < 0.116$

Experimentally challenging in LHCb because of the charged K* decay final state particles: K_s and π^0

B -> K_{res}g -> PPPg

- For a given intermediate resonance, the differential decay rate depends on helicity amplitude J_μ and the photon direction θ

$$\frac{d\Gamma(B\to K_{res}\gamma\to P_1P_2P_3\gamma)}{ds\,ds_{13}\,ds_{23}\,d\cos\theta} \propto |\vec{\mathcal{J}}|^2(1+\cos^2\theta)+\lambda_\gamma\, 2\,\mathrm{Im}\left[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)\right]\cos\theta$$

but for multiple resonances (up to spin 2)

$$\frac{d\Gamma(\sum B\to K_{res,i}\gamma\to P_1P_2P_3\gamma)}{ds\,ds_{13}\,ds_{23}\,d\cos\theta} \propto \sum_{j=0,\mathrm{even}}^{4} a_j(s_{13},s_{23})\cos^j\theta+\sum_{j=1,\mathrm{odd}}^{3}\lambda_\gamma\, a_j(s_{13},s_{23})\cos^j\theta$$

PhiGamma & KstGamma

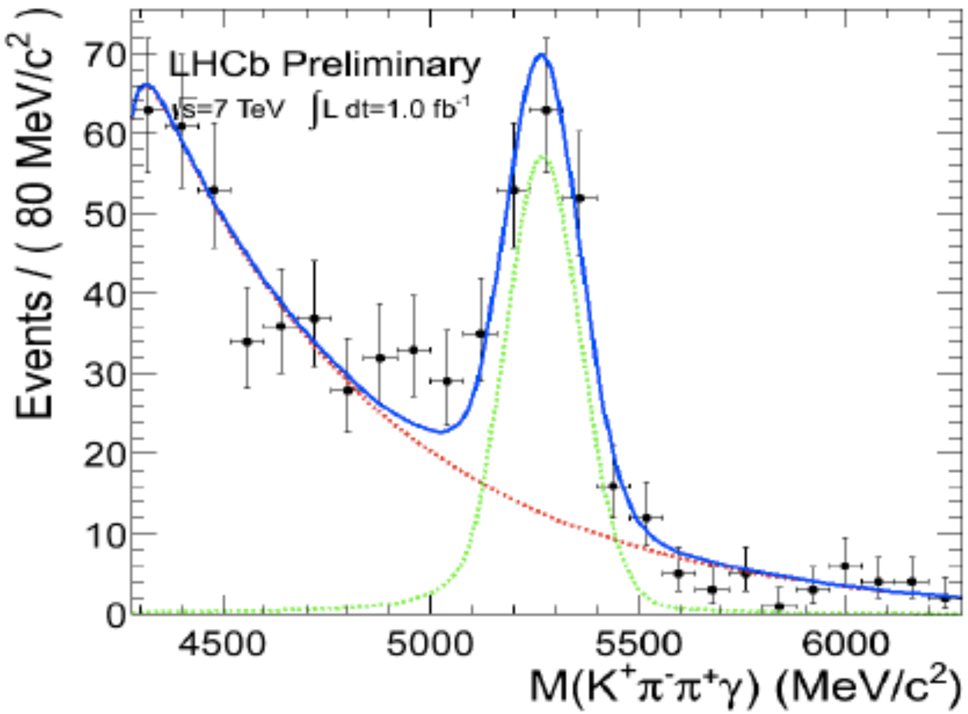
		$B \to K^* \gamma$	$B_s \to \phi\gamma$
Track IP χ^2		> 25	> 25
$p_{T,track}$	(MeV)	> 500	> 500
K PID_K		> 5	> 5
K $PID_K - PID_p$		> 2	> 2
π PID_K		< 0	-
meson ΔM_{PDG}	(MeV)	< 50	< 9
meson vertex χ^2		< 9	< 9
γ E_T	(MeV)	> 2600	> 2600
γ CL		> 0.25	> 0.25
π/γ separation		> 0.5	> 0.5
$p_{T,B}$	(MeV)	> 3000	> 3000
B IP χ^2		< 9	< 9
B helicity		< 0.8	< 0.8
B isolation $\Delta\chi^2$		> 0.5	> 0.5

$B \to VP\gamma$

Use of selections of the $B \to V\gamma$ channels as starting point but bearing in mind that:

- There are more tracks → more info available
- Less combinatorial background

Still very preliminary results but pretty reasonable fit performance



PhiKGamma selection

		Stripping cut	Selection cut
B meson	Impact parameter chi2	15	9
	Vertex quality chi2	-	9
	Pointing angle (rad)	0.02	0.02
	Isolation	-	2
	Flight distance chi2	64	100
	Transverse momentum (MeV)	-	3000
photon	Likelihood vs. pi0	-	0.5
	Transverse momentum (MeV)	2500	2600
	Likelihood vs. electrons	0.25	0.25
phi	Vertex quality chi2	15	9
	Deviation from the nominal mass (MeV)	15	9
tracks	Minimum impact parameter chi2	16	25
	Likelihood vs. pions	-	0
	Likelihood vs. protons	-	-2
	Transverse momentum (MeV)	300	500

Old Selection

Very preliminary

New selection

		New selection cut
B meson	Impact parameter chi2	6
	Vertex quality chi2	9
	Pointing angle (rad)	0.014
	Isolation	10
	Flight distance chi2	100
	Transverse momentum (MeV)	3000
photon	Likelihood vs. pi0	0.5
	Transverse momentum (MeV)	2600
	Likelihood vs. electrons	0.25
phi	Vertex quality chi2	6
	Deviation from the nominal mass (MeV)	9
tracks	Minimum impact parameter chi2	25 (75 for bachelor)
	Likelihood vs. pions	0
	Likelihood vs. protons	-2
	Transverse momentum (MeV)	500 (800 for bachelor)
Kinematics	$M(\phi K_b)$ (MeV)	2500

Radiative decays: backgrounds

arXiv:1209.0313

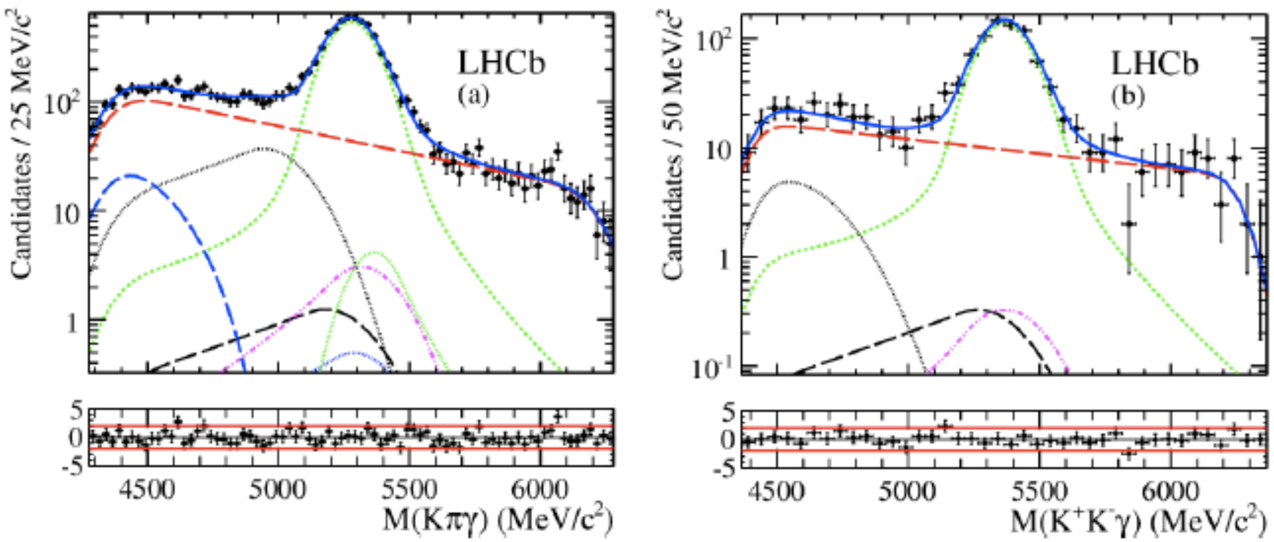
Generic background contamination:

- Combinatorial background
- Partially reconstructed $b \to s\gamma$ decays
- Partially reconstructed $b \to c(X + hh\pi^0)$

Specific peaking backgrounds:

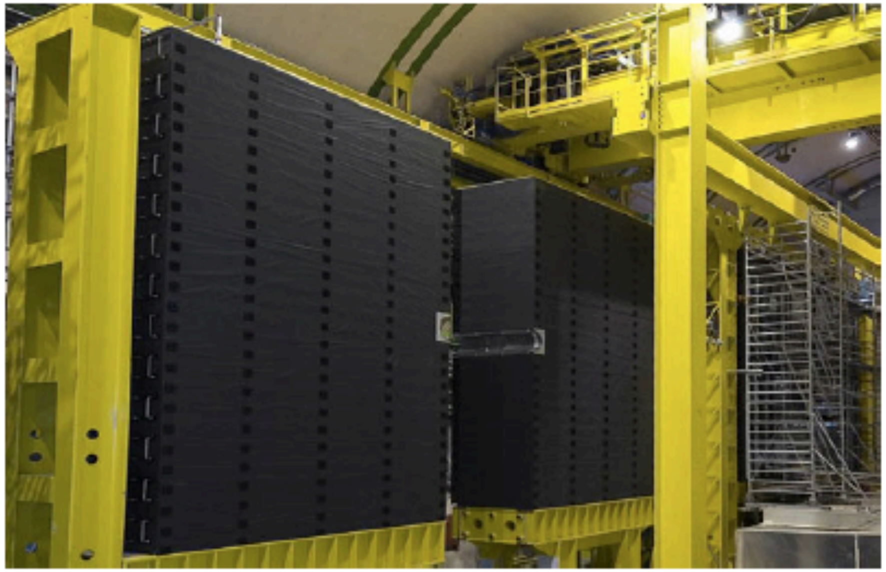
- b-baryons $\Lambda_b \to \Lambda^*(K^- p)\gamma$
- Charmless $B_{d,s} \to h^+h^-\pi^0$
- Irreducible $b \to d\gamma : B_s \to K^{*0}\gamma$

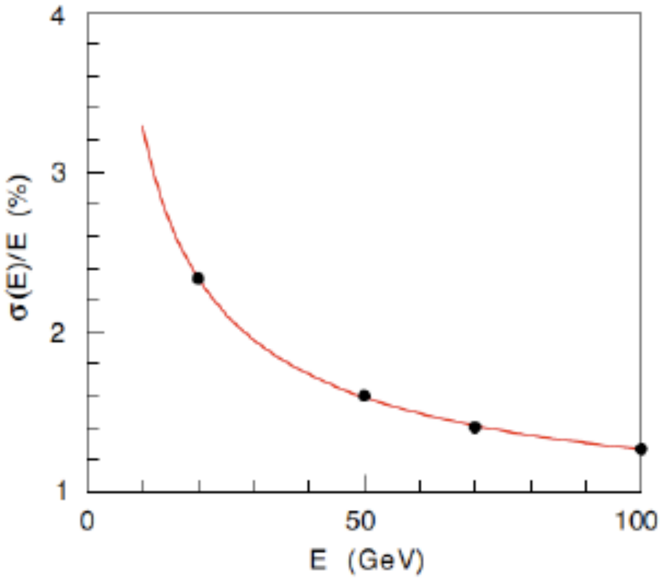
No trivial side-bands shape: threshold effect due to different Ecal/photon calibration



Radiative challenges

Much QCD background due to *pp* collisions (instead of *ee*)
B mass peak resolution given by the ECal resolution (about 90MeV), much larger than the one for tracks (about 20MeV)





Lambda_b -> Lambda*(X) gamma

The photon polarization depends on the Lambda* spin
L*(1520) is not established:

- J=3/2 , which means it may not be sensitive to photon polarization
- Contamination from L*(1600), highly unknown

L*(1670) and L*(1690) still unknown