$B_s \to \phi\gamma$ time dependent CPV

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for the LHCb collaboration

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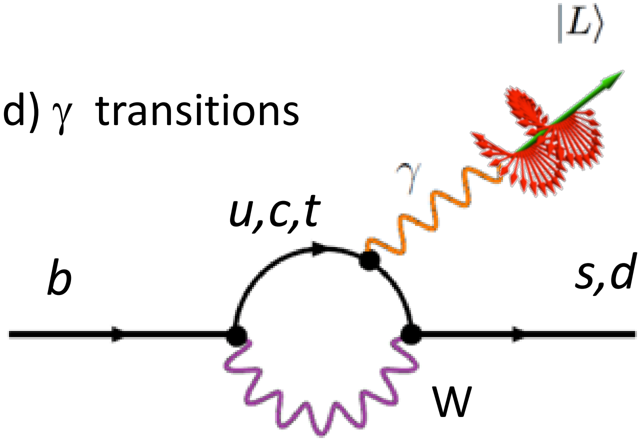
Outline

- Mixing-induced CPV from radiative decays
- Radiative decays at LHCb
- First time dependent analysis of $B_s \to \phi\gamma$ decays
- Results and interpretation
- Prospects
- Conclusions

CPV from radiative decays

- Radiative decays of B mesons are rare $b \to (s,d)\,\gamma$ transitions with small BR ~ 10^{-5} - 10^{-6}

- In the SM the photons emitted are polarized left-handed, with a small right-handed correction $O(m_{d,s}/m_b)$



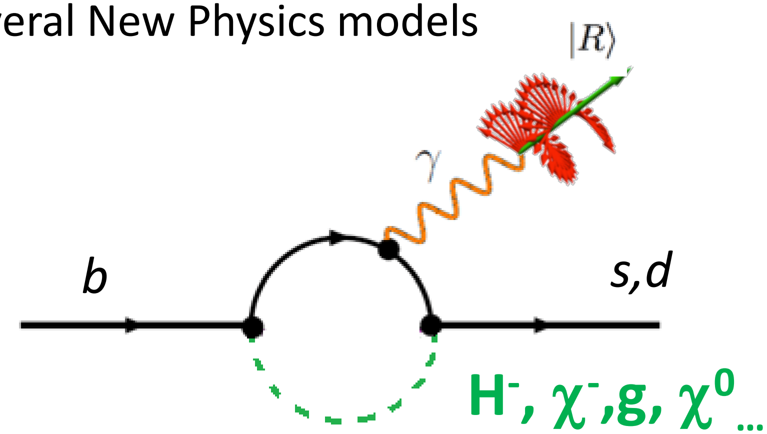
- Oscillations will be observable in radiative B meson decays if:

$\to$ Both neutral $B_{(s)}$ and $\overline{B}_{(s)}$ decay into the same exclusive CP state: Ex: $B_{(s)} \to V\gamma$

$\to$ The photons produced in these decays are a mixture of right and left-handed polarizations, as predicted by several New Physics models

[Atwood, Gronau, Soni PRL79(1997)185]

Measuring the oscillation of radiative B meson decays one has access to the photon polarization information



CPV from radiative decays

- The time dependent decay rate for a $B_{(s)} \to V\gamma$ a and $\overline{B}_{(s)} \to V\gamma$:

$$\Gamma_{B,\bar{B}}(t) = \mathcal{B}_0 e^{-\Gamma t}[\cosh(\frac{\Delta\Gamma}{2}t) - A^{\Delta} \sinh(\frac{\Delta\Gamma}{2}t) \pm C \cos(\Delta m\ t) \mp S \sin(\Delta m\ t)]$$

Only accessible for B_s decays

$\Delta\Gamma_d \sim 0$

$\Delta\Gamma_s \sim 0.081 \pm 0.011\ ps^{-1}$

Need to tag the flavour of the initial $B_{(s)}$

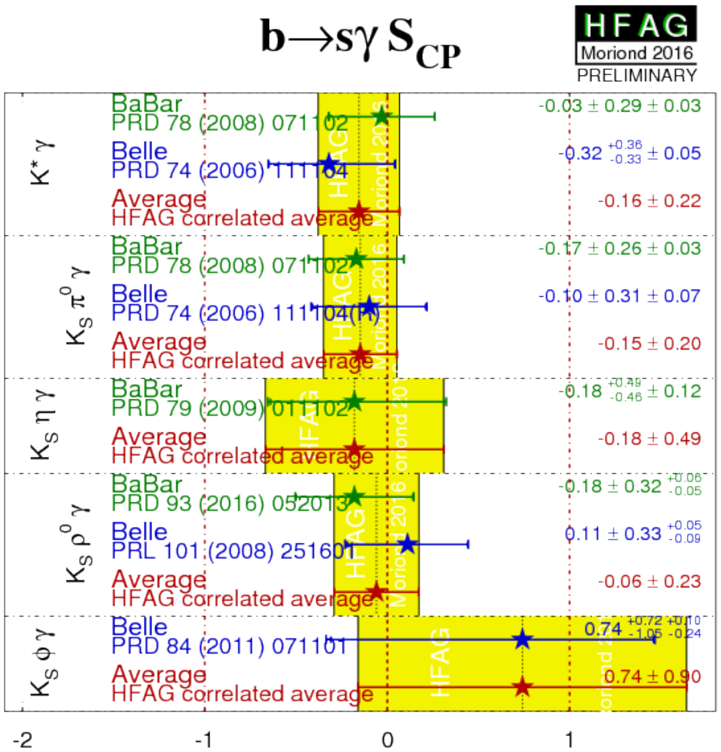
$$A^{\Delta} = \frac{2\,\mathrm{Re}[\frac{q}{p}(\bar{\mathcal{A}}_L\mathcal{A}_L^* + \bar{\mathcal{A}}_R\mathcal{A}_R^*)]}{|\mathcal{A}_L|^2 + |\bar{\mathcal{A}}_L|^2 + |\mathcal{A}_R|^2 + |\bar{\mathcal{A}}_R|^2}$$

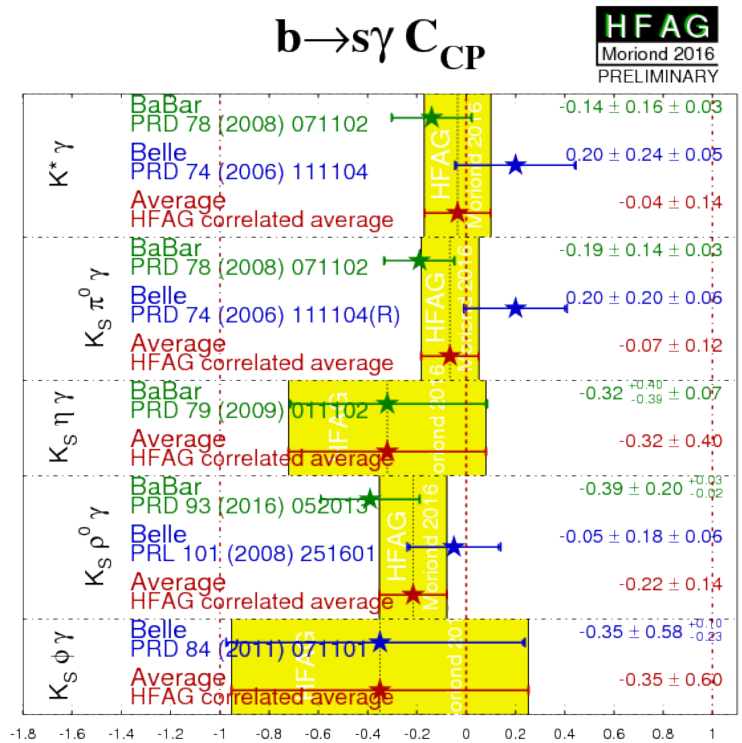
$$S = \frac{2\,\mathrm{Im}[\frac{q}{p}(\bar{\mathcal{A}}_L\mathcal{A}_L^* + \bar{\mathcal{A}}_R\mathcal{A}_R^*)]}{|\mathcal{A}_L|^2 + |\bar{\mathcal{A}}_L|^2 + |\mathcal{A}_R|^2 + |\bar{\mathcal{A}}_R|^2}$$

$$C = \frac{(|\mathcal{A}_L|^2 + |\mathcal{A}_R|^2) - (|\bar{\mathcal{A}}_R|^2 + |\bar{\mathcal{A}}_L|^2)}{|\mathcal{A}_L|^2 + |\bar{\mathcal{A}}_L|^2 + |\mathcal{A}_R|^2 + |\bar{\mathcal{A}}_R|^2}$$

CPV from radiative decays

- At present only information from *S* and *C* parameters in the B_d system





→ Results in agreement with the SM predictions

CPV from radiative decays

- The time dependent decay rate for a $B_{(s)} \to V\gamma$ a and $\overline{B}_{(s)} \to V\gamma$:

$$\Gamma_{B,\overline{B}}(t) = \mathcal{B}_0 e^{-\Gamma t}[\cosh(\frac{\Delta\Gamma}{2}t) - A^{\Delta} \sinh(\frac{\Delta\Gamma}{2}t) \pm C \cos(\Delta m\ t) \mp S \sin(\Delta m\ t)]$$

→ **For the $B_s \to \phi\gamma$ decay channel the SM predictions are:**

[Muheim, Xie, Zwicky, PLB664(2008)174]

$$A^{\Delta}_{SM} = 0.047 \pm 0.025 + 0.015_{O(\alpha_s)} \qquad S_{SM} = 0 \pm 0.002$$

→ Left-Right Symmetric models: A^{Δ} up to ~ 0.7

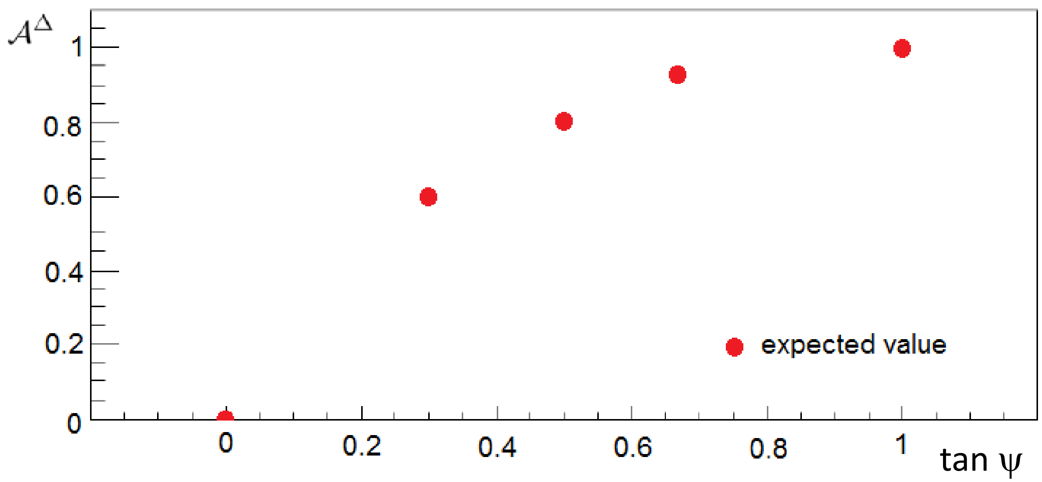
[Atwood, Gronau, Soni PRL79(1997)185]

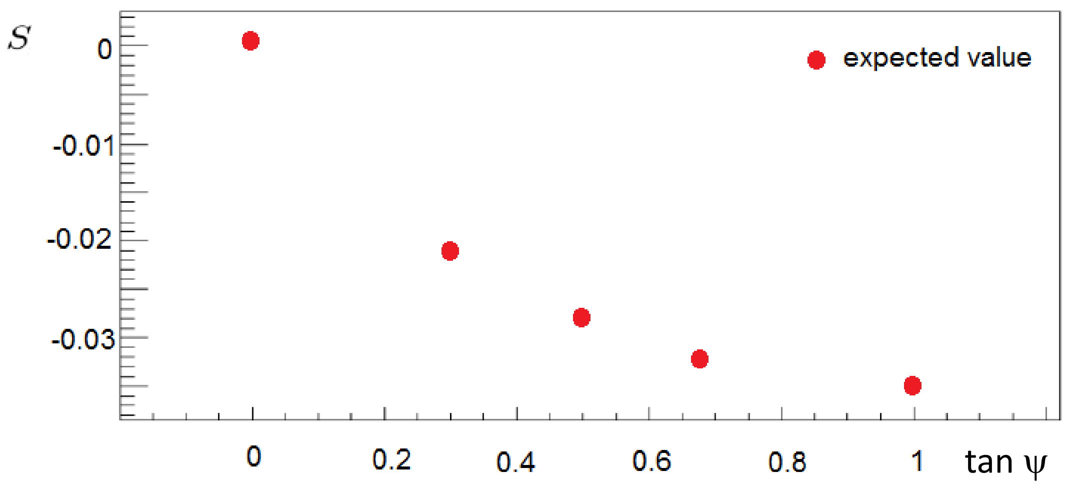
→ **Fraction of anomalous polarized photons ~ 40%**

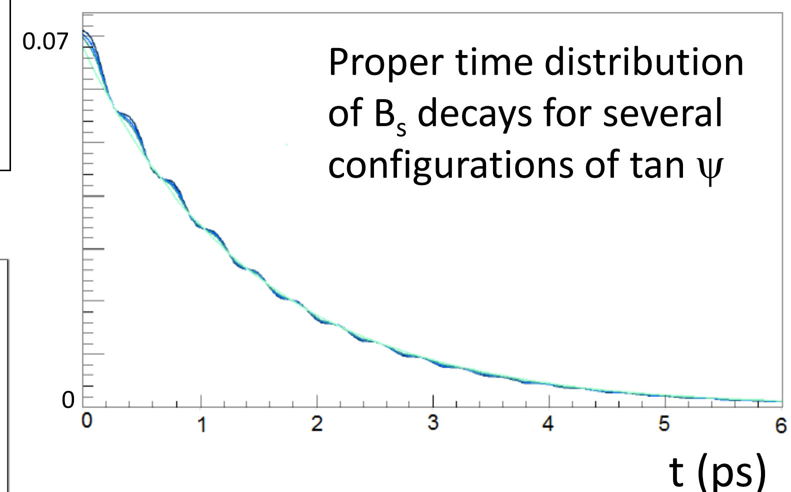
CPV from radiative decays

- Dependence of A^{Δ} and S parameters with the fraction of anomalous polarized photons

$$\tan\psi \equiv \left| \frac{\mathcal{A}\left(B_s \to \phi\,\gamma_L\right)}{\mathcal{A}\left(B_s \to \phi\,\gamma_R\right)} \right|$$

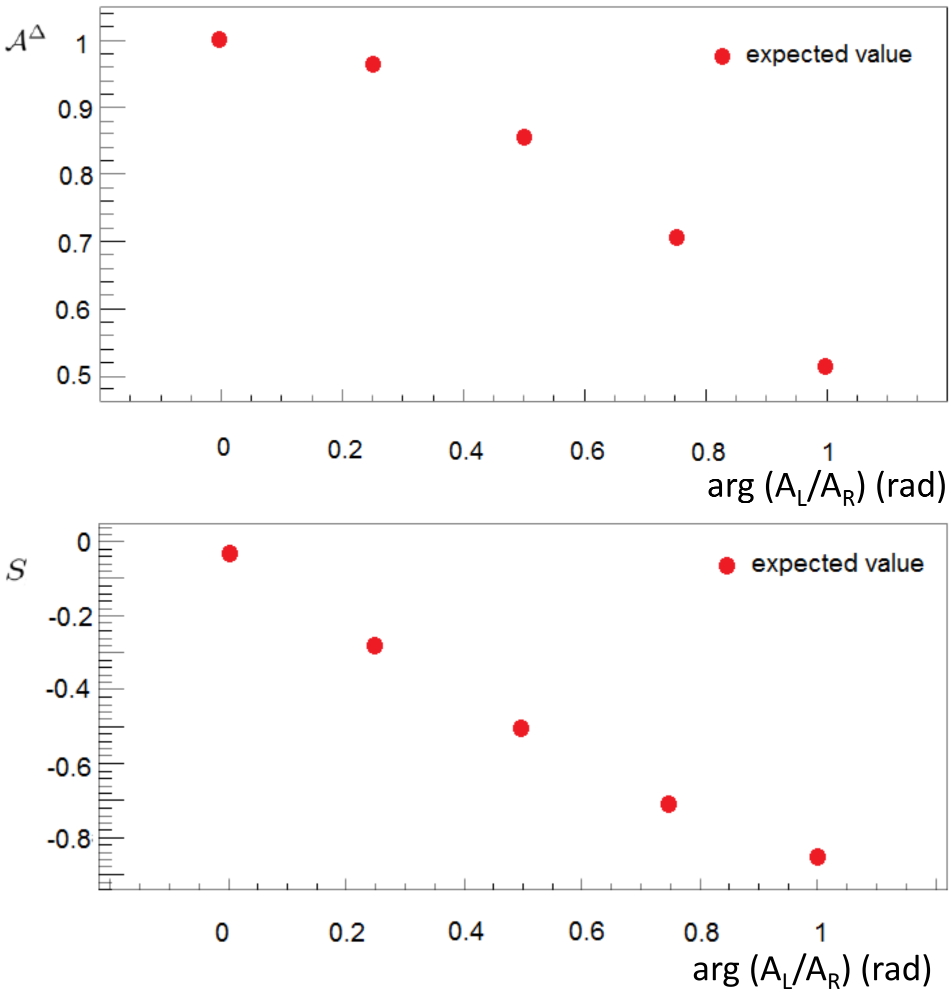


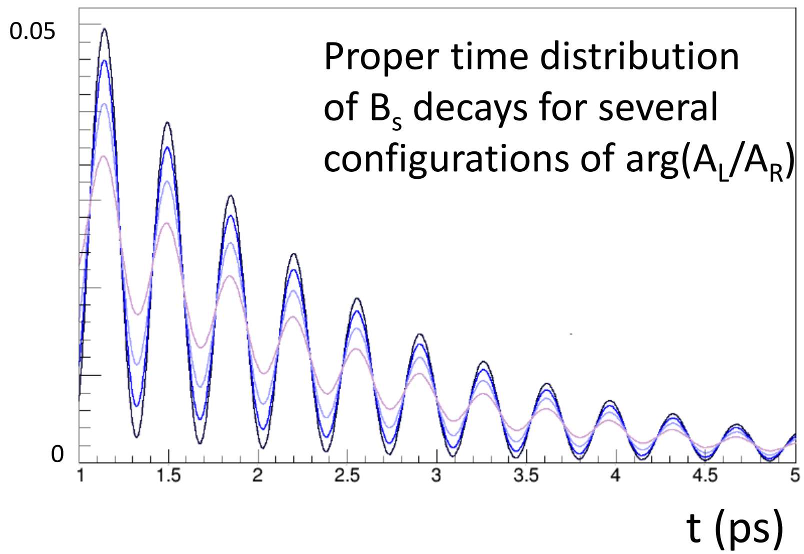




CPV from radiative decays

- Dependence of $\mathcal{A}^{\Delta}$ and S parameters with the relative phase of anomalous polarized photons (assuming 50% of A_L)

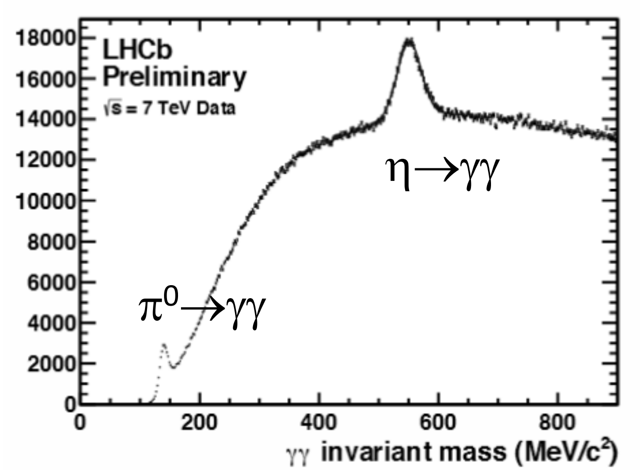


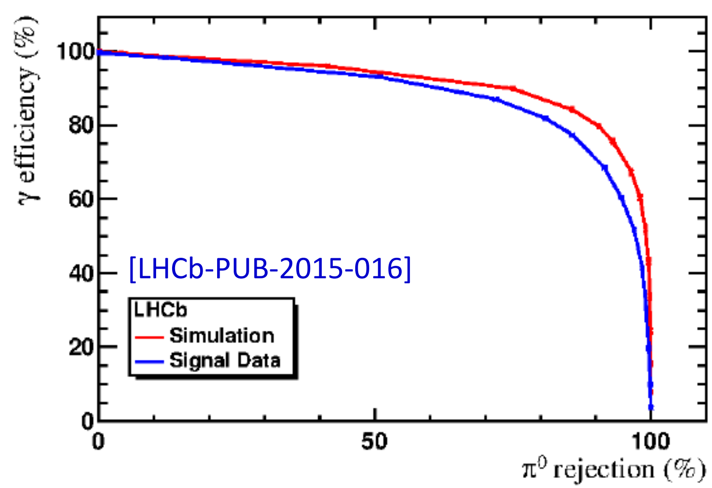


Radiative decays at LHCb

A difficult task in pp collisions:

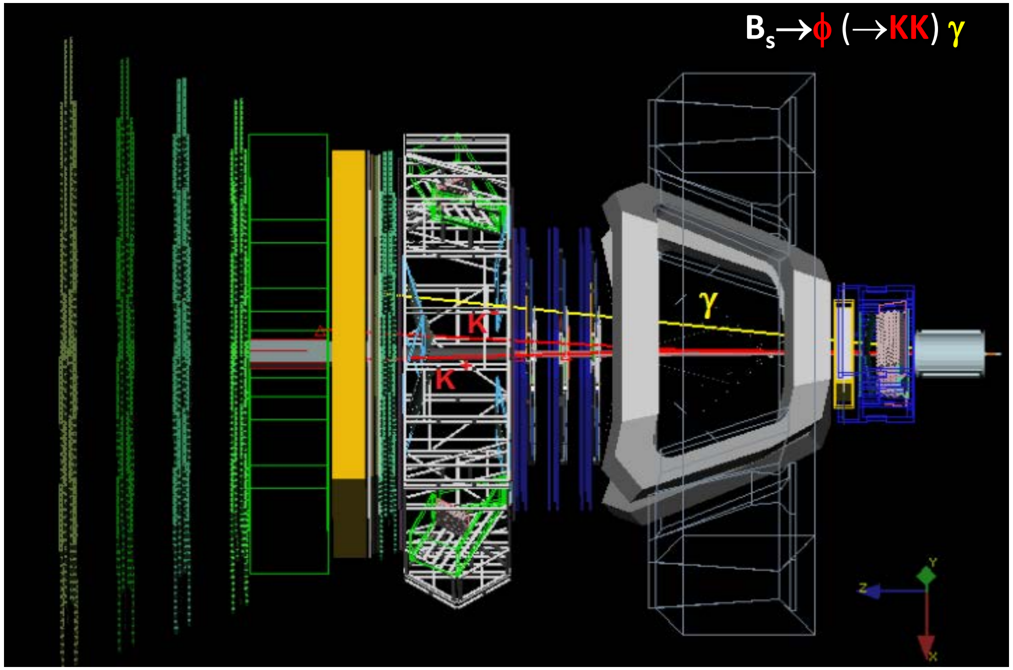
- Huge amount of combinatorial photons in the calorimeter: ~ 10 γ's/event
- Large calorimeter occupancy, large background
  - $\rightarrow$ Use neutral PID to separate neutral EM shower from hadronic and electron deposits.
- High energy photons (p_T > 2.5GeV) from $\pi^0 \rightarrow \gamma\gamma$ merge in the same calorimeter cells.
  - $\rightarrow$ Special multivariate tool for separation using info from shower shapes
- Photons give low constraints in radiative B decays
  - $\rightarrow$ No origin vertex, decay info limited by the ECAL resolution



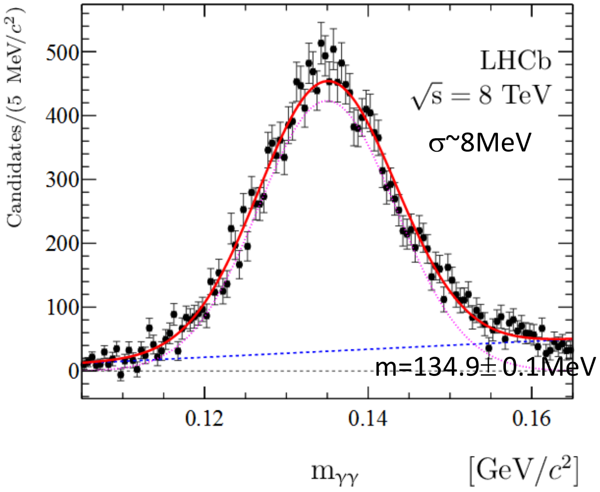


Radiative decays at LHCb

Photon reconstruction @ LHCb



$\pi^0 \to \gamma\gamma$ reconstruction



(From $B \to J/\psi K^{(*)}$ samples)

[CERN-LHCb-PROC-2015-009]

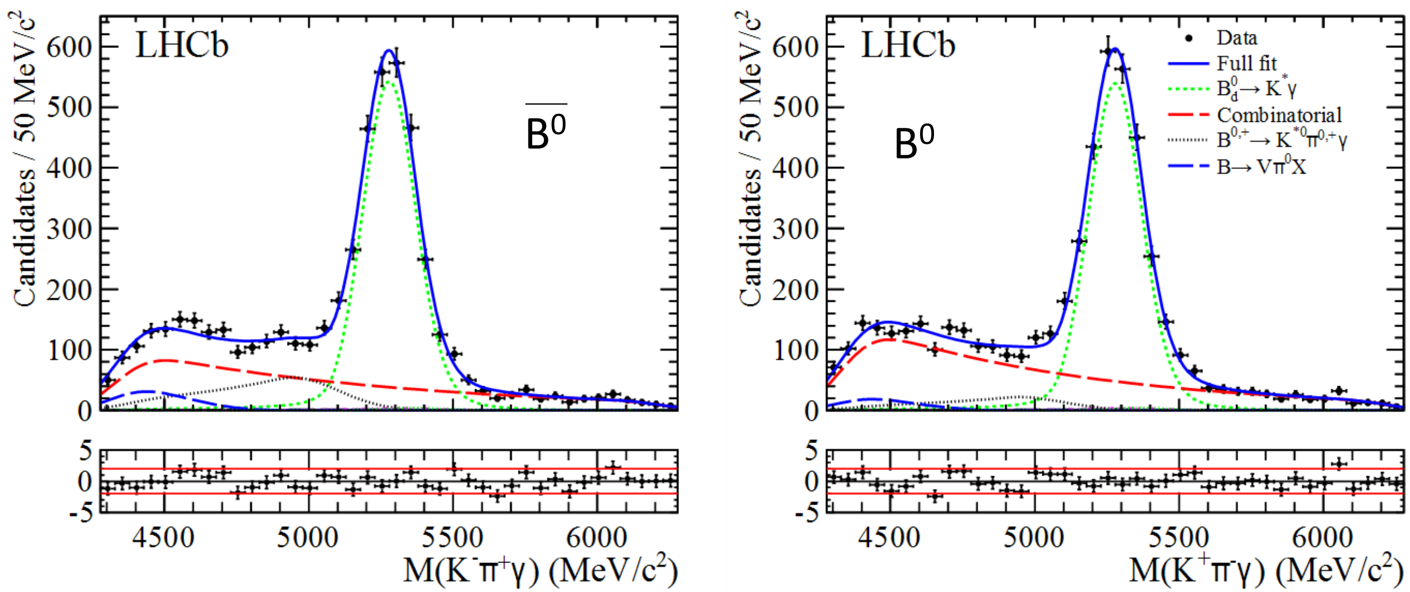
- Calorimetric photons: converted to a e^+e^- pair after the magnet or unconverted
  - → High energy photons from B decays: B mass resolution σ~92 MeV/c^2
- Converted photons: $\gamma \to e^+e^-$ materialization
  - → Small fraction ~ 20%
  - → Better B mass resolution, σ~30 MeV/c^2

Radiative decays at LHCb

First measurements @ LHCb:

[Nuc. Phys. B 867 (2013) 1-18]

5279 ± 93 $B_d \to K^*\gamma$
691 ± 36 $B_s \to \phi\gamma$



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

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

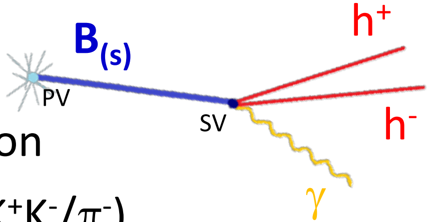
(this with 1fb^{-1}, update with 3fb^{-1} soon)

Time dependent analysis of $B_s \to \phi\gamma$

- Untagged analysis → *C* and *S* terms cancel, access to the A^{Δ} parameter

$$\Gamma_{B_s^0 \to \phi\gamma}(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\Delta\Gamma_s t/2\right) - \mathcal{A}^{\Delta}\sinh\left(\Delta\Gamma_s t/2\right)\right]$$

- Use $B^0 \to K^*\gamma$ (with $K^{*0} \to K^+\pi^-$) as control channel of $B_s \to \phi\gamma$ (with $\phi \to K^+K^-$)



Experimentally:

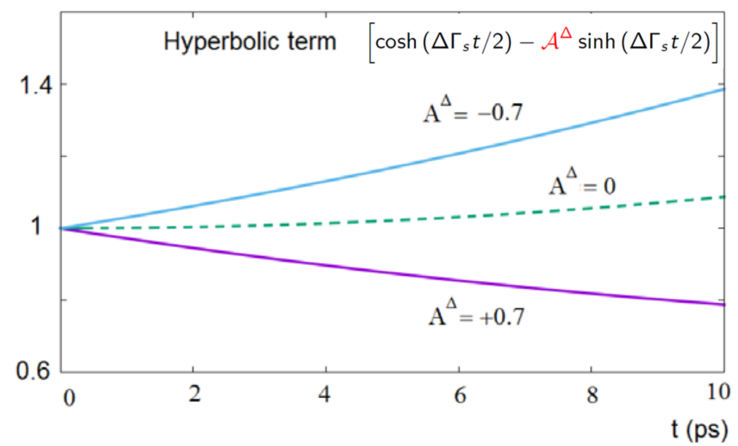
Similar topology: similar trigger, reconstruction and selection

→ a high-energy photon and two tracks of opposite sign (K^+K^-/π^-)

Theoretically:

$$\Gamma_{B^0 \to K^{*0}\gamma}(t) \propto e^{-\Gamma_d t}$$

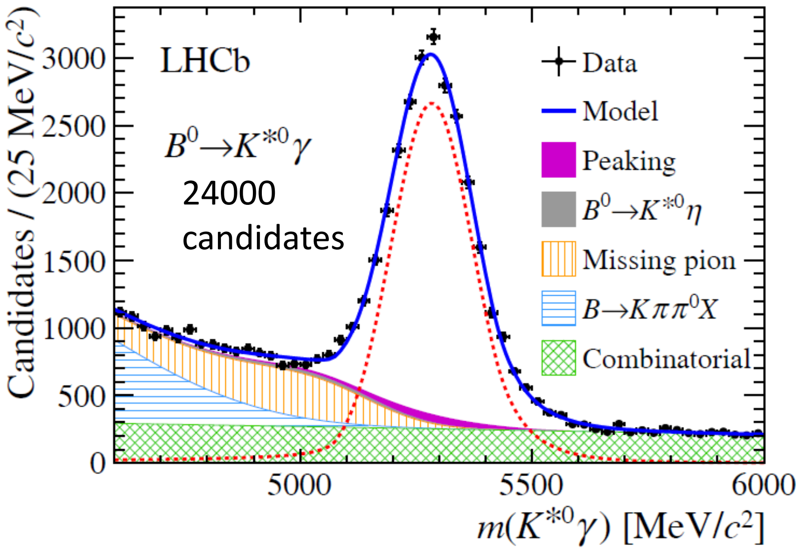
→ $B^0 \to K^{*0}\gamma$ is flavour specific
→ $\Delta\Gamma_d \sim 0$
→ $\Gamma_d \sim \Gamma_s$

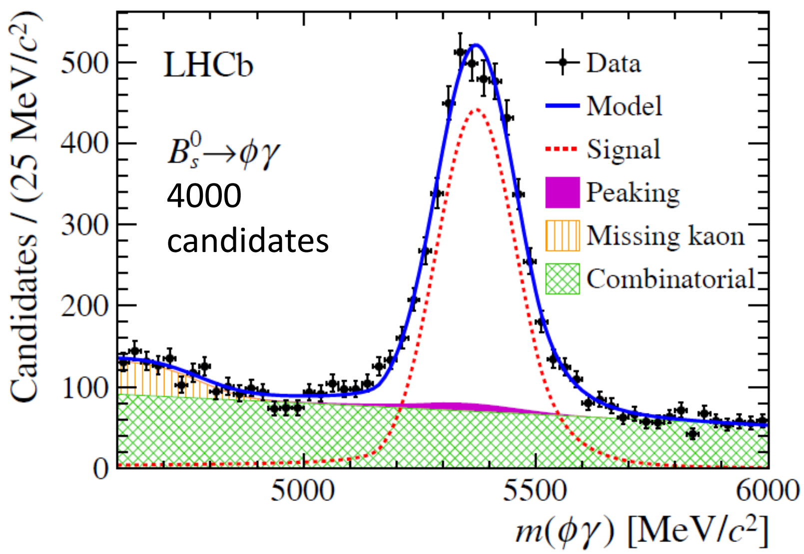


Not affected by new physics: Key to control the experimental effects

Time dependent analysis of $B_s \to \phi\gamma$

- Background subtraction from mass fit (*sFit* technique):





Signal model: modified Crystal Ball, with tails in both sides of the peak

Background model:

- Combinatorial (~15%)*: First-order polynomial
- Partially reconstructed (~5% for $K^*\gamma$)*: ARGUS convolved with a Gaussian
- Peaking (~2%)* included in the signal, contribution corrected afterwards

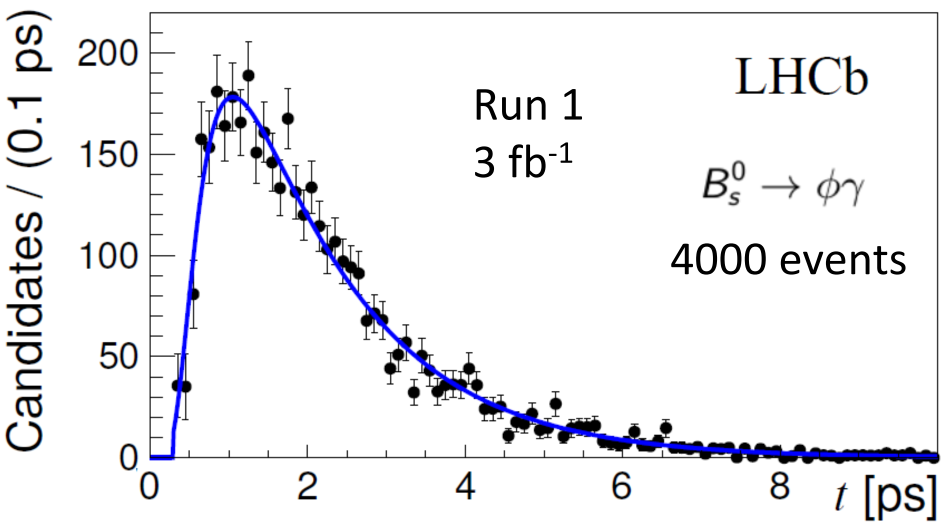
(* In the signal region)

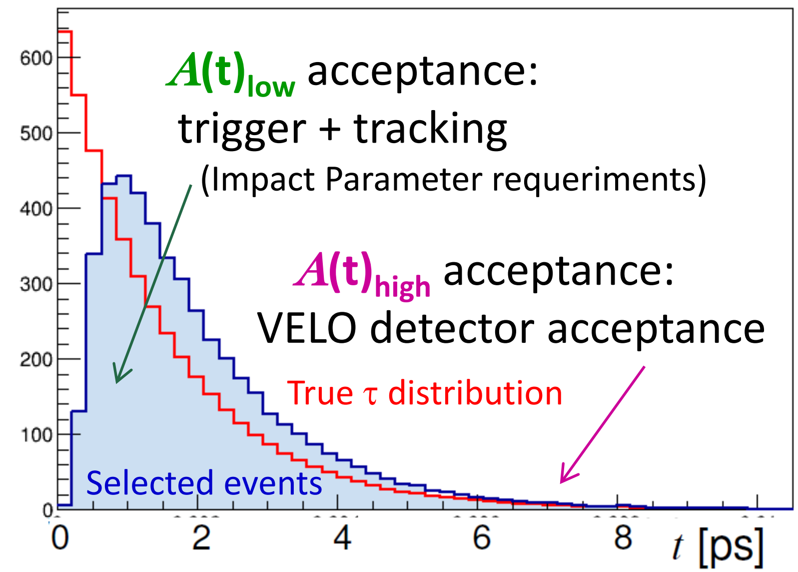
Time dependent analysis of $B_s \to \phi\gamma$

- The decay time is measured from the B momentum and flight distance, after a full kinematical fit of the decay channel

$$\Gamma_{Bs}(t_r) \text{ measured } = \mathcal{A}(t) \cdot \Gamma_{Bs}(t; A^{\Delta}) \otimes R(t,t_r)$$

Untagged decay time distribution:





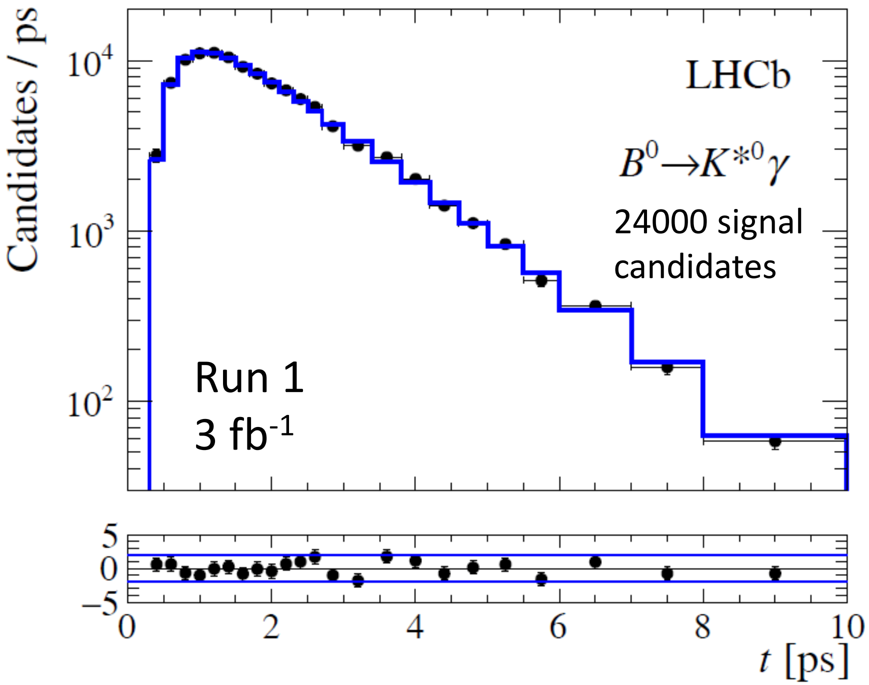
- Need to control the proper time acceptance

$$\mathcal{A}(t) = \frac{at^n}{1+at^n} \times (1+\beta t)$$

- Effect of proper time resolution negligible (σ_t~ 60-100 fs)

Results and interpretation

- Acceptance constrained from simulation after validating with the $B \to K^* \gamma$ sample:



$$\Gamma_{B^0 \to K^{*0}\gamma}(t) \propto e^{-\Gamma_d t}$$

Result of the fit:

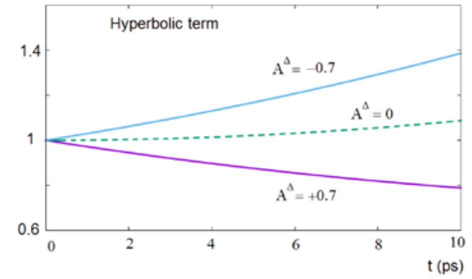
$$\tau_{B^0} = 1.524 \pm 0.013_{\text{stat}}\ \text{ps}$$

Compatible with PDG:

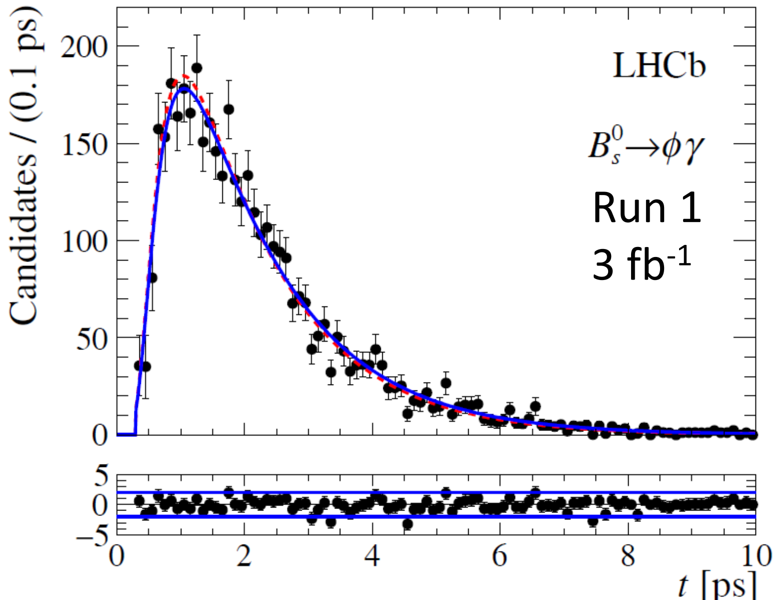
$$\tau_{B^0} = 1.520 \pm 0.004\,\text{ps}$$

(Checked also a null test if we consider an unphysical A^{Δ} term)

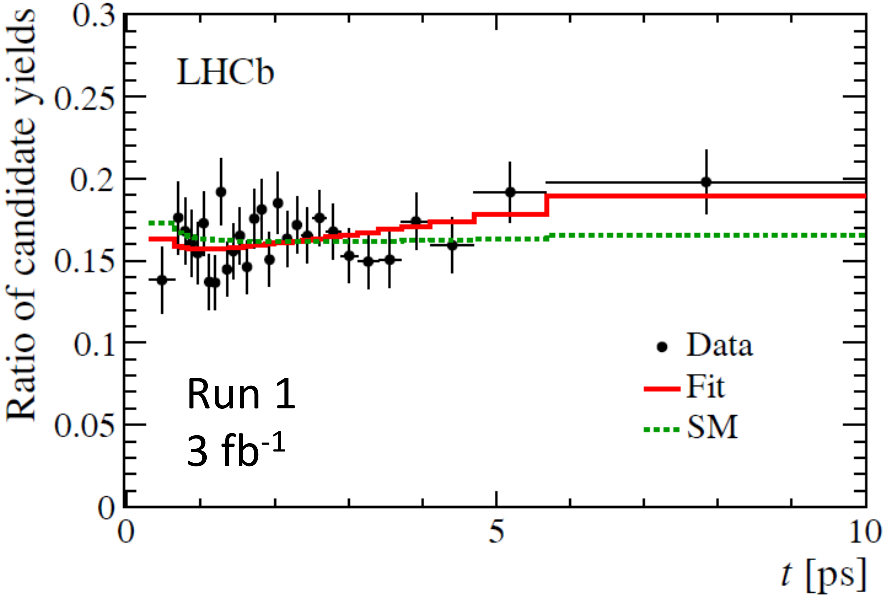
Results and interpretation



- Fit procedure: blinded unbinned simultaneous fit to $B_s \to \phi\gamma$ and $B \to K^*\gamma$ samples
- Alternatively, a blinded binned fit to the $B_s \to \phi\gamma$ / $B \to K^*\gamma$ ratio



$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}$$



$$\mathcal{A}^{\Delta} = -0.85\,^{+0.43}_{-0.46}$$

- Compatible results, verified with toy simulations
- Same sensitivity considering the $\sigma_{A^{\Delta}}$ correlation with the value of A^{Δ}
- Statistical uncertainty includes uncertainties from external parameters ($\Delta\Gamma_s$, Γ_s)

Results and interpretation

- Use as nominal the unbinned fit (suitable for a next tagged analysis)

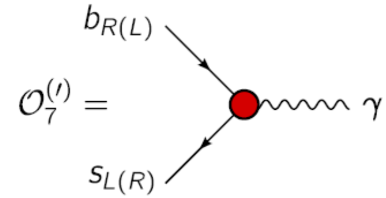
$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}$$

- Systematic uncertainties:

Source	$+\sigma(A^{\Delta})$	$-\sigma(A^{\Delta})$
Correlations mass vs decay time in bkg	0.15	0.15
Peaking backgrounds	0.02	0.05
Mass modelling: signal	0.03	0.03
Mass modelling: combinatorial	0.07	0.07
Mass modelling: partial bkg	0.10	0.10
Acceptance function (from simulation)	0.13	0.05
Resolution function	0.01	0.01
Total	+ 0.23	- 0.20

$\rightarrow$ expected to be reduced with Run 2 data

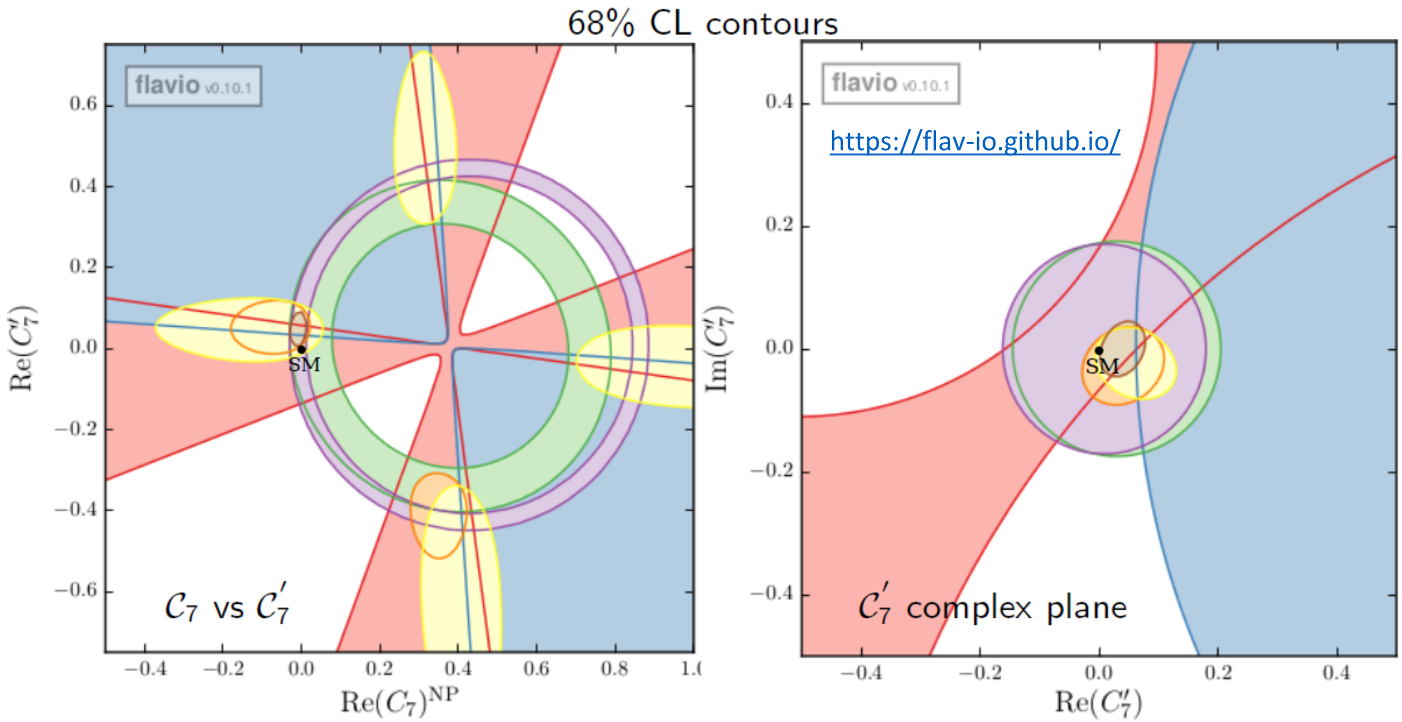
Results and interpretation



- In terms of the Wilson coefficients C_7 and C_7':

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big(\underbrace{C_i \mathcal{O}_i}_{\text{left-handed}} + \underbrace{C_i' \mathcal{O}_i'}_{\text{right-handed}} \Big) + h.c.$$

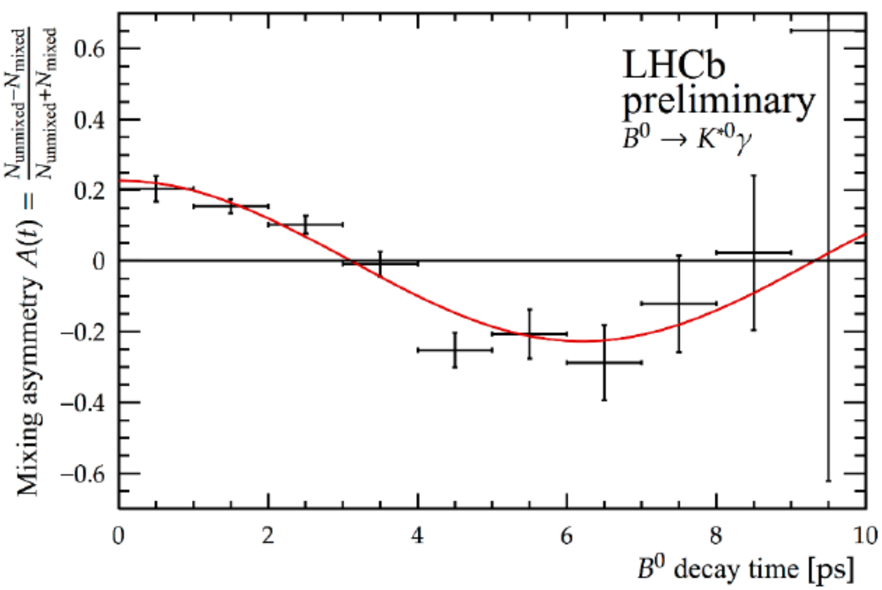
$$\mathcal{A}^{\Delta} \simeq \frac{2\,\mathrm{Re}\,(e^{-i\phi_s}\, \mathcal{C}_7\, \mathcal{C}_7')}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

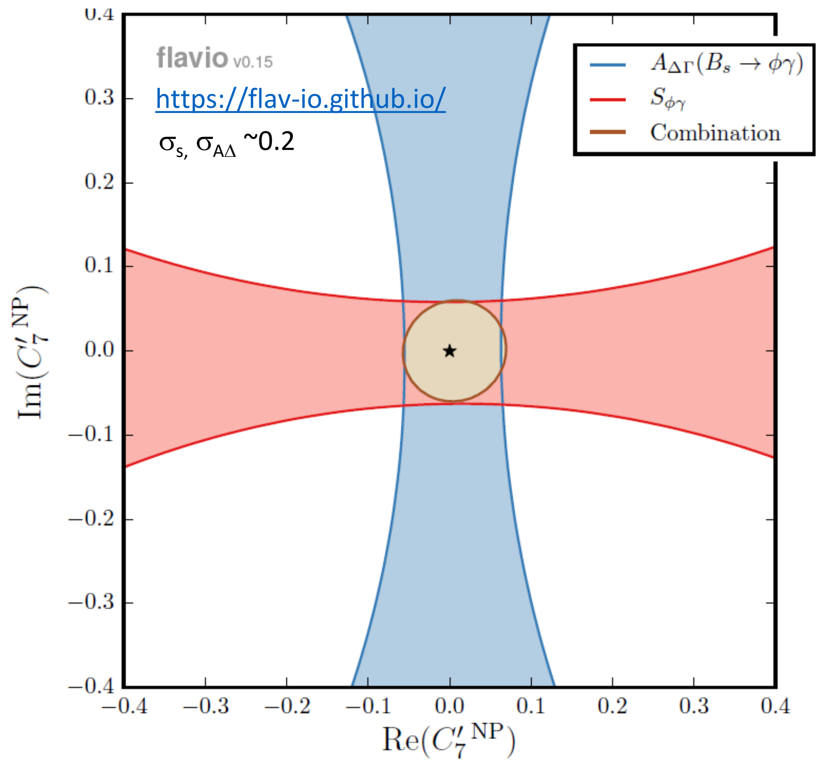


All combined
$\mathcal{A}^{\Delta}(B_s^0 \to \phi\gamma)$ [LHCB-PAPER-2016-034]
$\mathrm{ang}(B^0 \to K^{*0} e^+ e^-)$ [LHCb: JHEP 04(2015)064]
$\mathrm{ang}(B^0 \to K^{*0} \mu^+ \mu^-)$ [LHCb: JHEP 1602(2016)104]
$S_{K*\gamma}$ [HFAG: arXiv:1207.1158]
$\mathrm{BR}(B \to X_s\gamma)$ [HFAG: arXiv:1207.1158]
$\mathrm{BR}(B_s^0 \to \phi\gamma)$ [LHCb: Nucl.Phys. B867(2013)1-18]
[Belle: PRD91 1(2015)011101]

Prospects

- Add Run2, and use events with flavour tagging information
- Good performance of flavour tagging for radiative $B_{(s)}$ decays ($\varepsilon_{eff} > 5\%$)





- Important constraints on new physics when including the *S* parameter!

Conclusions

- First time dependent analysis of a radiative B_s decay, using LHCb data

  [LHCb-PAPER-2016-034, arXiv:1609.02032v1, submitted to PRL]

- Measurement of the A^{Δ} parameter:

$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20}$$

- Compatible within 2σ with the SM predictions: $\mathcal{A}^{\Delta}_{\mathrm{SM}} = 0.047\,^{+0.029}_{-0.025}$

- Statistically limited, uncertainty will be reduced quite soon adding Run 2 data

- Info from flavour tagging will be added to extract the *S* and *C* CPV parameters

Thanks!