Radiative decays at LHCb

Carlos Sánchez Mayordomo
IFIC (CSIC / U. Valencia)

VII CPAN Days
Segovia

1-Dec-2015

Analyses

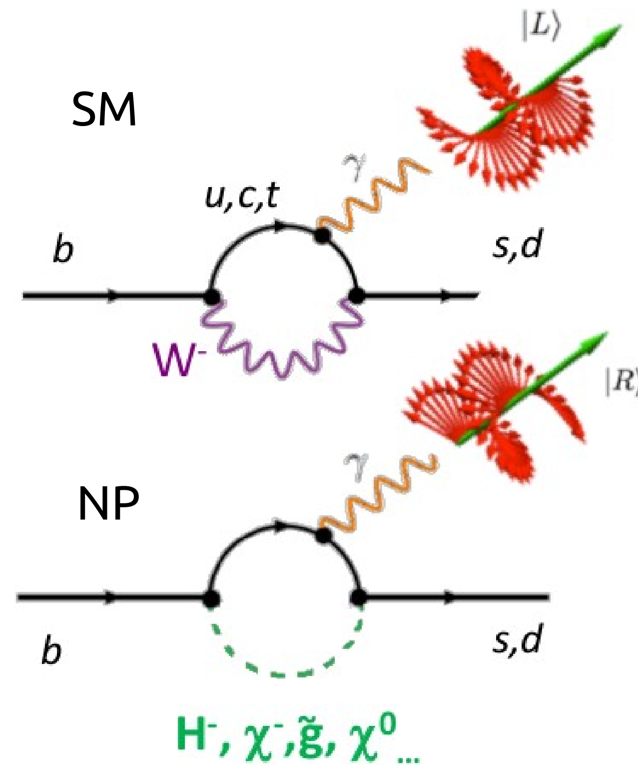
- Photon polarization
  - $B^+ \to K^+ \pi^- \pi^+ \gamma$ **LHCb [PRL 112, 161801 (2014)]**
  - $B^0 \to K^{*0} e^+ e^-$ **LHCb [JHEP04(2015)064]**
  - $B_s \to \phi\gamma$ **(work in progress...)**
- Search for decay channels
  - $B_{(s)} \to J/\Psi\gamma$ **LHCb [arXiv:1510.04866]**

Motivation

- **b→sγ** transition is strongly supressed in the SM, allowed as a FCNC involving penguin diagrams

- **Photons** in such transitions are predicted to be **left-handed in the SM** due to $W^{\pm}$ interaction, within small corrections $O(m_s/m_b)$

- **Right-handed component** enhanced in some extensions of the SM (like **MSSM** or **LRSM**), after the inclusion of heavy particles in the electroweak penguin **[Everett et al. JHEP(2002) 022; D. Atwood et al. PRL79(97)185]**



- Wilson coefficients $\mathbf{C_7^{(\prime)}}$ related to left- (right)-handed polarized photons

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{tq}}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

$$\mathcal{O}_7^{(\prime)} = \frac{\alpha}{4\pi} m_b [\bar{s}\sigma_{\mu\nu} P_{R(L)} b] F^{\mu\nu}$$

$$\boxed{r \equiv \frac{C_7'}{C_7} \simeq \frac{m_s}{m_b}}$$

Motivation

Ways to measure the photon polarization at LHCb

- Angular analyses
  - 3-body + photon in the final state: $B^+ \to K^+ \pi^- \pi^+ \gamma$
  - Electron pair from a virtual photon: $B^0 \to K^{*0} e^+ e^-$ in the low-q^2 region
  - B-baryon decays: $\Lambda_b \to \Lambda \gamma$
- Time-dependent analyses
  - Common final state for B and $\overline{B}$, to have interference between mixing and decay ($B_{(s)} \to V\gamma$, $V \to h^+h^-$): $B_s \to \phi\gamma$, $B^0 \to \rho\gamma$, $B^0 \to \omega\gamma$
    - B_s decays are more sensitive than B^0 decays ($\Delta\Gamma_s >> \Delta\Gamma_d$)
    - Not possible for LHCb to reconstruct the decay $B^0 \to K^{*0}(\to K_s \pi^0)\gamma$

Search for decays sensitive to NP

- *W* boson exchange diagrams: $B_{(s)} \to J/\Psi\gamma$

Motivation

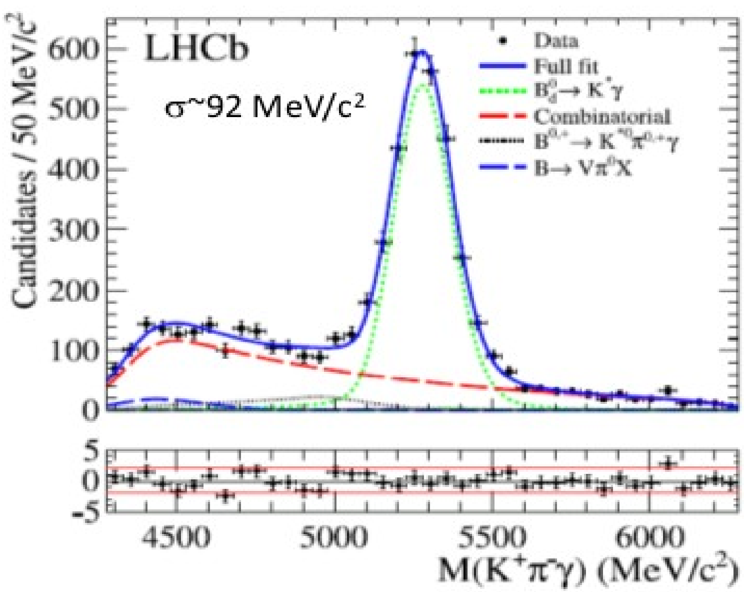
- Previous radiative measurements with 1 fb^{-1} at LHCb

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

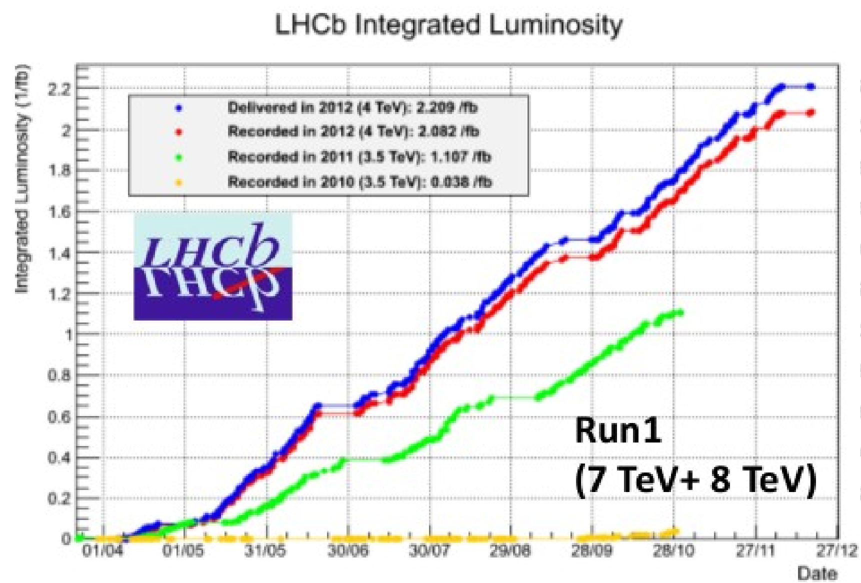
$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (0.8 \pm 1.7\,(\text{stat.}) \pm 0.9\,(\text{syst.}))\%.$$

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

- Challenges: Resolution of the reconstructed B mass determined by the photon momentum resolution



- Statistics: Currently we stored 3 fb^{-1} of data in Run1 (2011+2012), 8 fb^{-1} expected after Run2

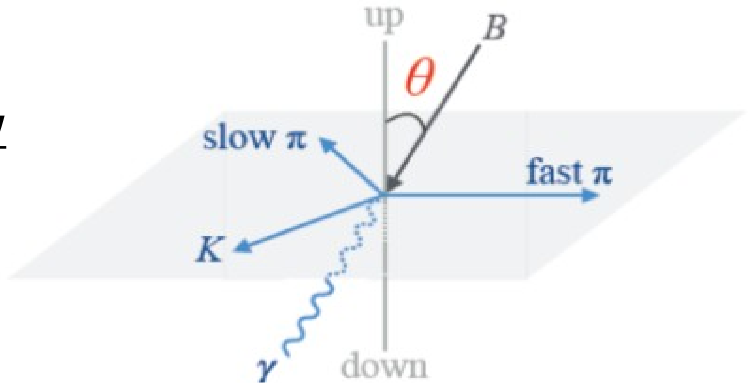


[LHCb collaboration, PRL 112, 161801 (2014)]

$B^+ \to K^+ \pi^- \pi^+ \gamma$

- The photon polarization can be extracted looking at the angular distribution of **$B^+ \to K_{res}(\to$3-body) γ** decays, when interference patterns are present in the resonance. The decay plane defines a direction for γ

- This allows to compute the up-down asymmetry A_{ud} between the number of photons in each side of the Kππ plane, which is proportional to the photon polarization λ_γ:



$$A_{ud} = \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}} \propto \lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}$$

(c_R and c_L are the right and left amplitudes)

- In the SM, λ_γ is predicted to be +1(-1) for $B(\overline{B})$, with small corrections of order $(m_s/m_b)^2$

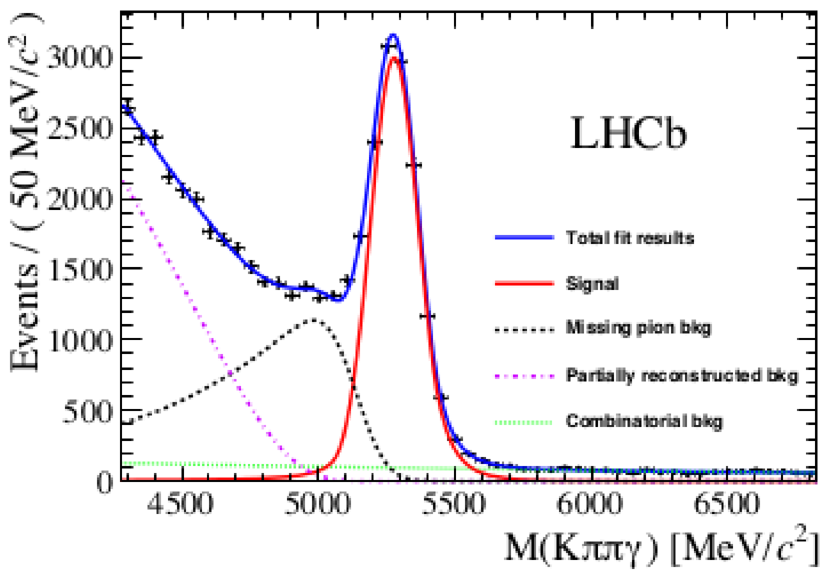
[LHCb collaboration, PRL 112, 161801 (2014)]

$B^+ \to K^+ \pi^- \pi^+ \gamma$

- Access to the photon polarization only possible if there is **interference** in the resonance $K_{res} \to K\pi\pi$ [Gronau et al, PRL88 (2002) 051802; Kou et al, PRD83 (2011) 094007]
- Several interferences contribute, so it is not possible to obtain a single value for λ_γ, however **the null hypothesis can be tested**

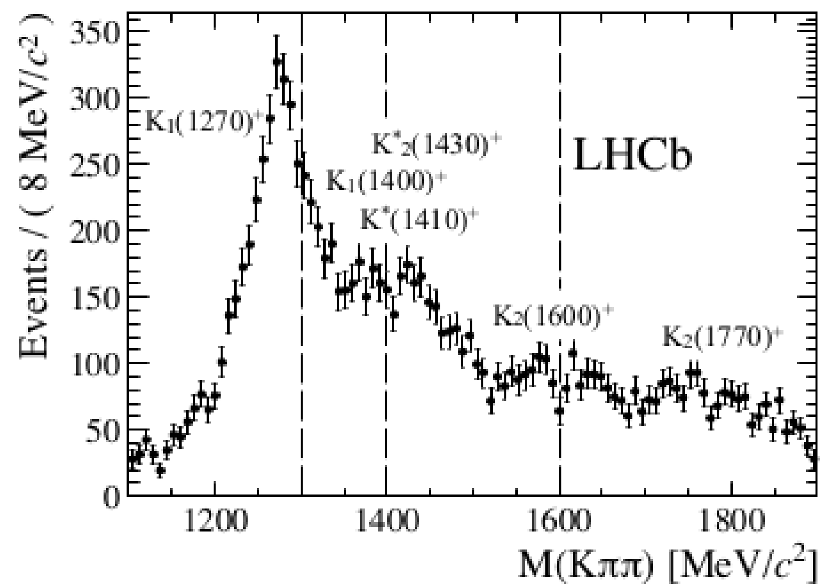
Fit to reconstructed B mass

~14,000 signal events



Four regions defined in M(Kππ)

[1.1, 1.9] GeV/c^2



The angular distribution is studied in each region

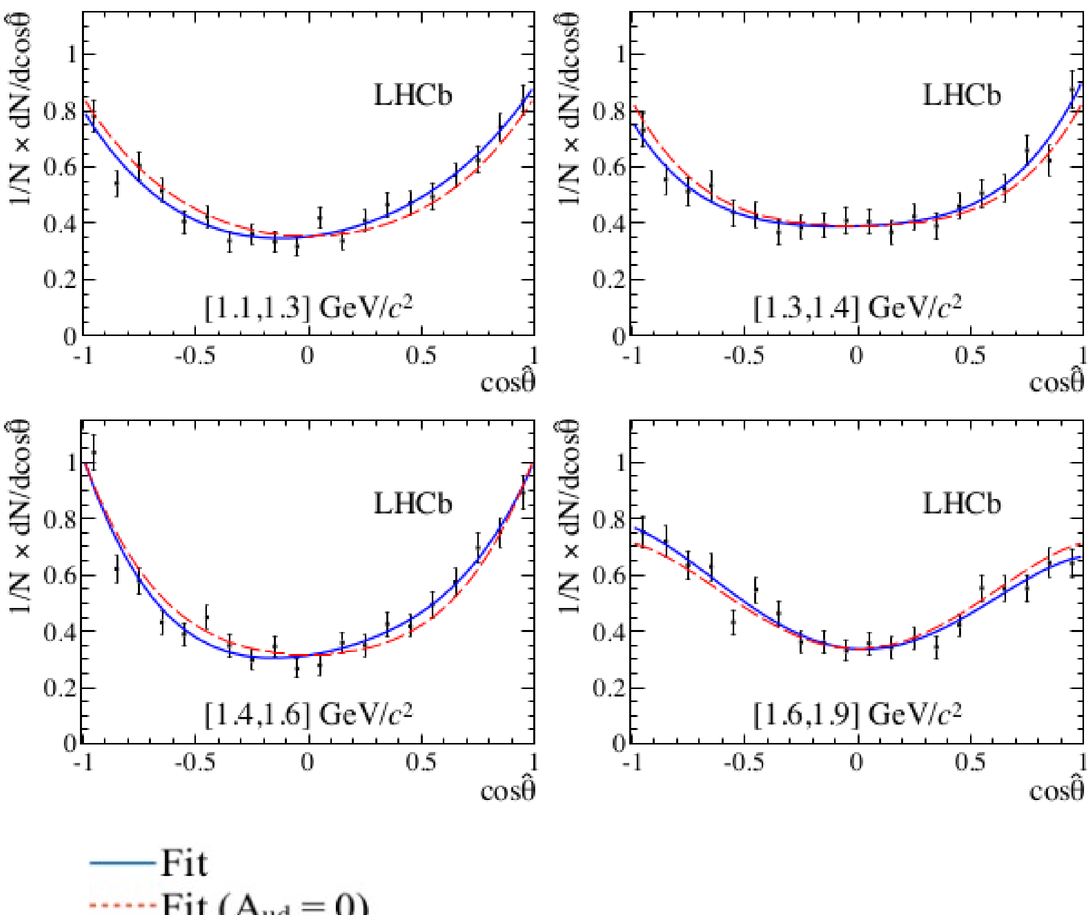
[LHCb collaboration, PRL 112, 161801 (2014)]

$B^+ \to K^+ \pi^- \pi^+ \gamma$

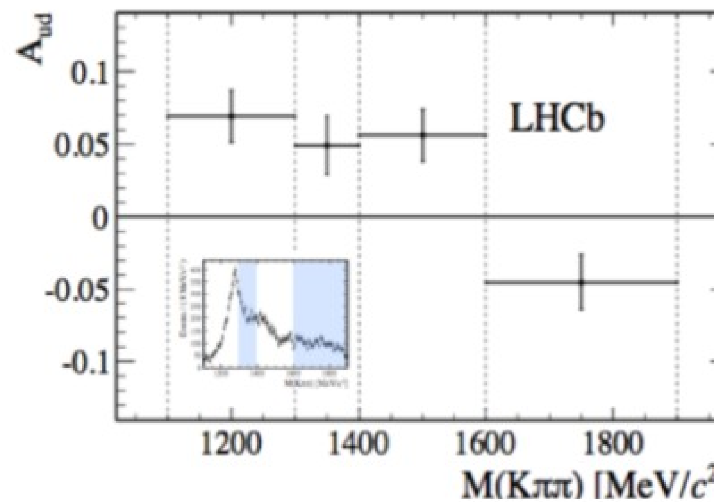
- Fit to the angular distribution $\cos\theta$. 4th-order polynomial

$$f(\cos\hat{\theta}; c_0 = 0.5, c_1, c_2, c_3, c_4) = \sum_{i=0}^{4} c_i L_i(\cos\hat{\theta}) \qquad A_{\rm ud} = \frac{c_1 - c_3/4}{2c_0}$$

- Asymmetries computed in each region



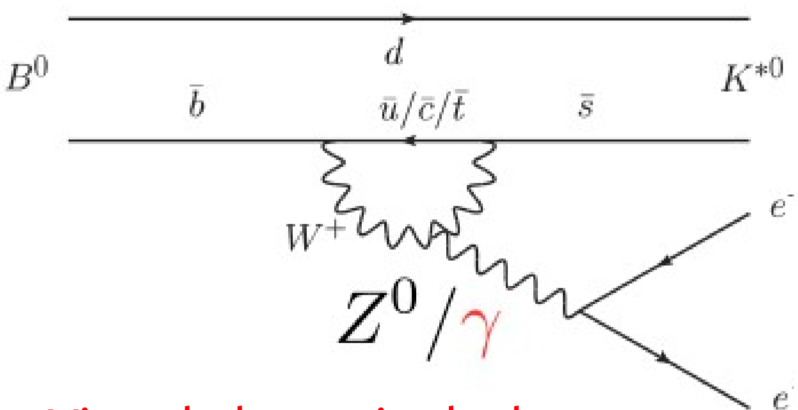
Non-zero $A_{\rm ud}$ found at 5.2σ significance



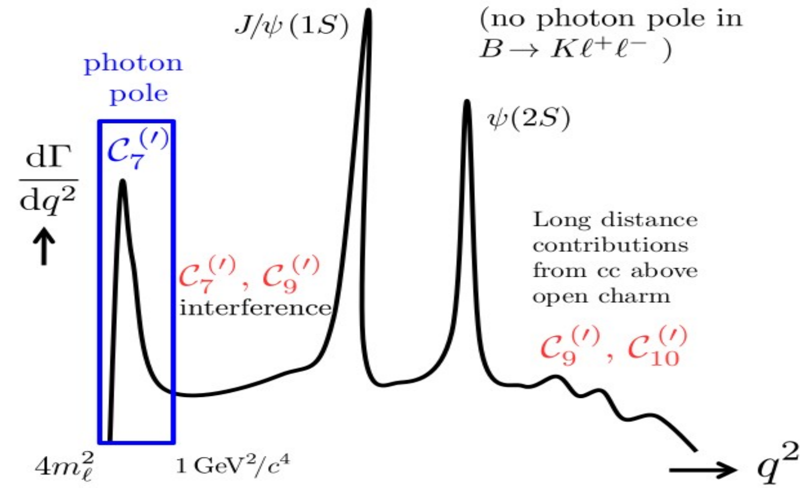
First observation of photon polarization in b→sγ transitions

$B^0 \to K^{*0} e^+ e^-$

- Angular analysis in $B^0 \to K^{*0} e^+ e^-$ at the photon pole ($q^2 < 1$ GeV²)



Virtual photon in the loop



Photon polarization

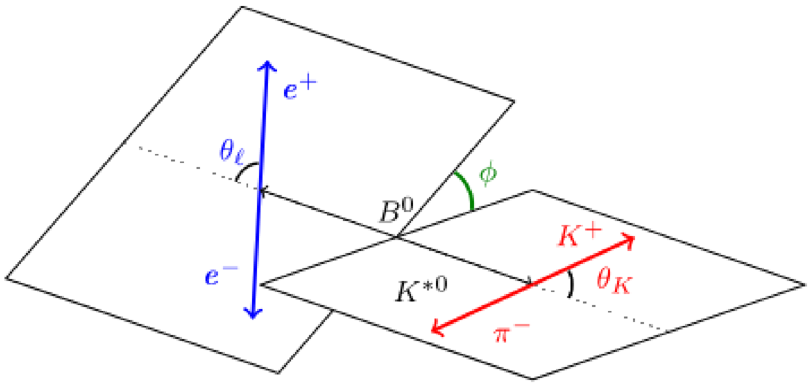
- $b \to s\ell^+\ell^-$ transition sensitive to the Wilson coefficients $C_7(')$, $C_9(')$, $C_{10}(')$
- Need to go as low as possible in q² to disentangle from $C_9(')$: <u>electrons</u>
- Competitive with radiative decays in the search of NP right-handed currents

$B^0 \to K^{*0} e^+ e^-$

- The differential decay can be described with three angles

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\,\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}} =$$

$$= \frac{9}{16\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K \; +$$
$$\left(\frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K - F_{\mathrm{L}}\cos^2\theta_K\right)\cos 2\theta_\ell \; +$$
$$\frac{1}{2}(1-F_{\mathrm{L}})\mathrm{A}_{\mathrm{T}}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2 \; +$$
$$(1-F_{\mathrm{L}})\mathrm{A}_{\mathrm{T}}^{\mathrm{Re}}\sin^2\theta_K\cos\theta_l \; +$$
$$\frac{1}{2}(1-F_{\mathrm{L}})\mathrm{A}_{\mathrm{T}}^{\mathrm{Im}}\sin^2\theta_K\sin^2\theta_\ell\sin 2\Big].$$



[D. Becirevic and E. Schneider Nucl. Phys. B 854 (2012) 321]

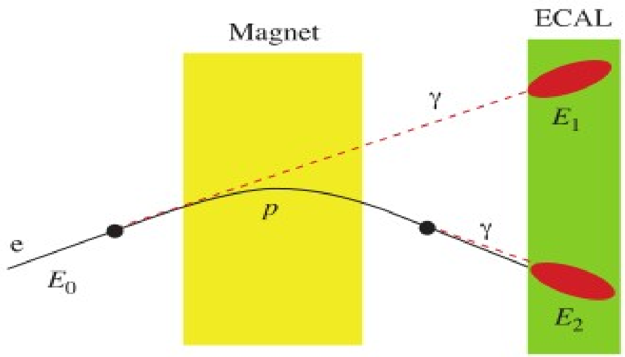
$\mathrm{A}_{\mathrm{T}}^{(2)}$ and $\mathrm{A}_{\mathrm{T}}^{\mathrm{Im}}$ in low q^2 are linked to photon polarization

$$\mathrm{A}_{\mathrm{T}}^{(2)}(q^2\to 0) = \frac{2\mathcal{Re}(\mathcal{C}_7\mathcal{C}_7^{\prime *})}{|\mathcal{C}_7|^2+|\mathcal{C}_7^\prime|^2}$$

$$\mathrm{A}_{\mathrm{T}}^{\mathrm{Im}}(q^2\to 0) = \frac{2\mathcal{Im}(\mathcal{C}_7\mathcal{C}_7^{\prime *})}{|\mathcal{C}_7|^2+|\mathcal{C}_7^\prime|^2}.$$

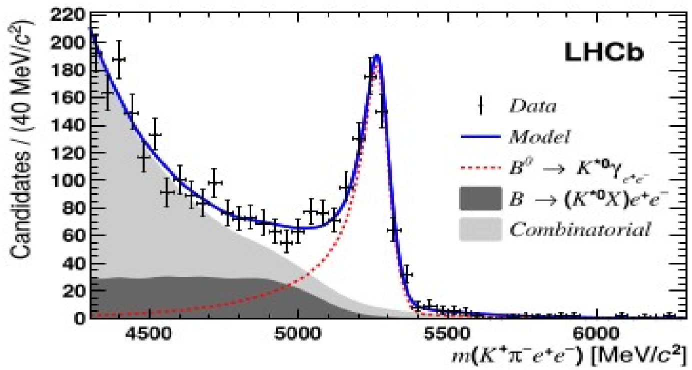
$B^0 \to K^{*0} e^+ e^-$

- Electron reconstruction at LHCb



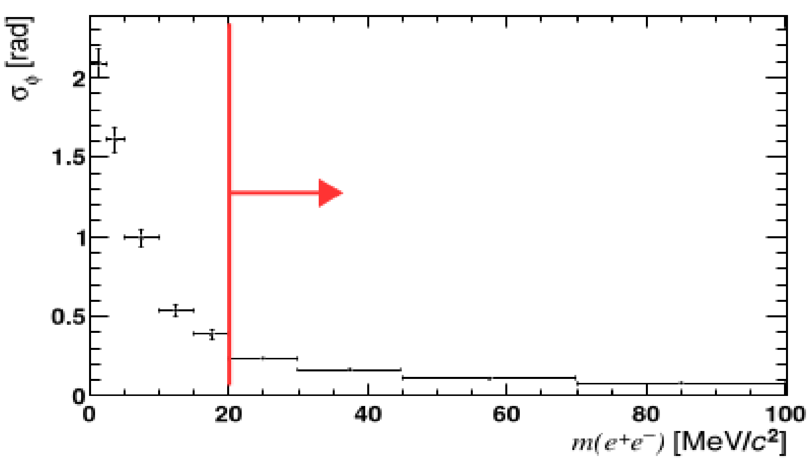
Mass resolution is affected by bremsstrahlung recovery

Validation channel $B^0 \to K^*\gamma$

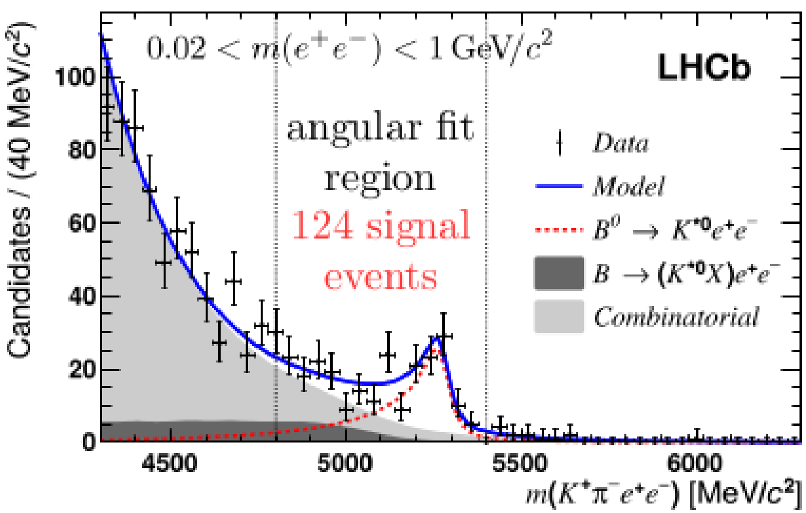


Long radiative tail at low masses

Cut at 20 MeV ($q^2 > 0.0004$ GeV²) to veto the $B^0 \to K^*\gamma$ with converted electrons

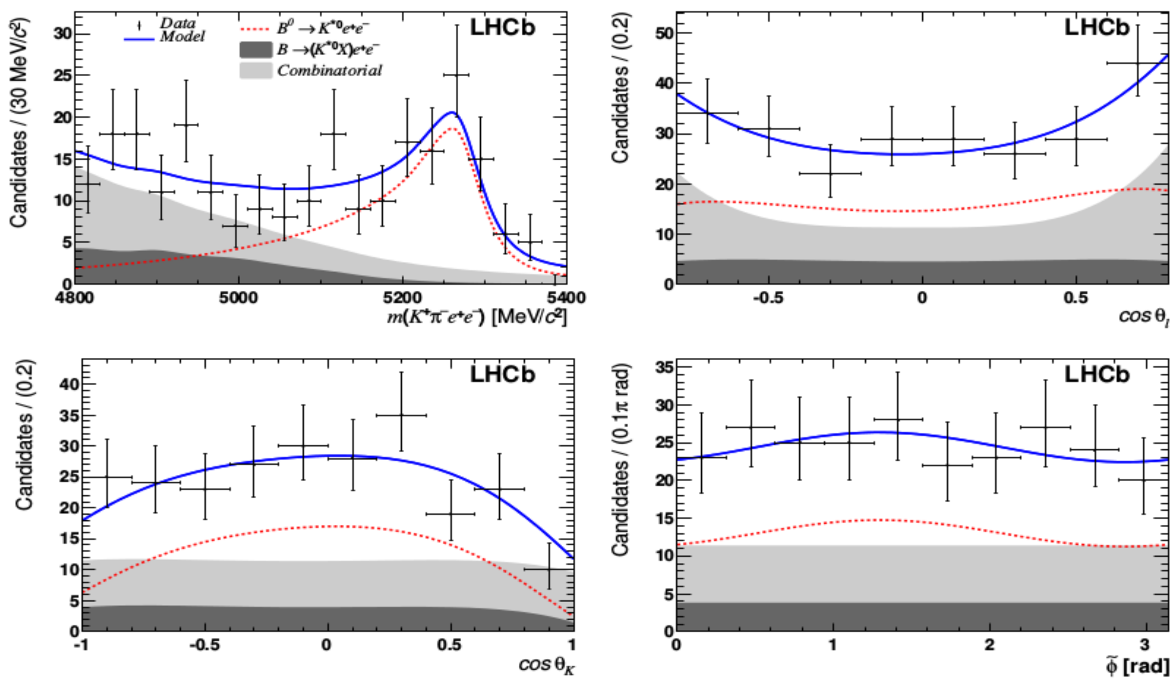


Signal channel $B^0 \to K^{*0} e^+ e^-$



$B^0 \to K^{*0} e^+ e^-$

- 4D angular analysis in mass and three angular variables



Results:

$$F_L = 0.16 \pm 0.06 \pm 0.03$$
$$A_T^{Re} = +0.10 \pm 0.18 \pm 0.05$$
$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_T^{Im} = +0.14 \pm 0.22 \pm 0.05$$

SM predictions:

$$F_L = 0.10^{+0.11}_{-0.05}$$
$$A_T^{Re} = -0.15^{+0.04}_{-0.03}$$
$$A_T^{(2)} = +0.03^{+0.05}_{-0.04}$$
$$A_T^{Im} = (-0.2^{+1.2}_{-1.2}) \times 10^{-4}$$

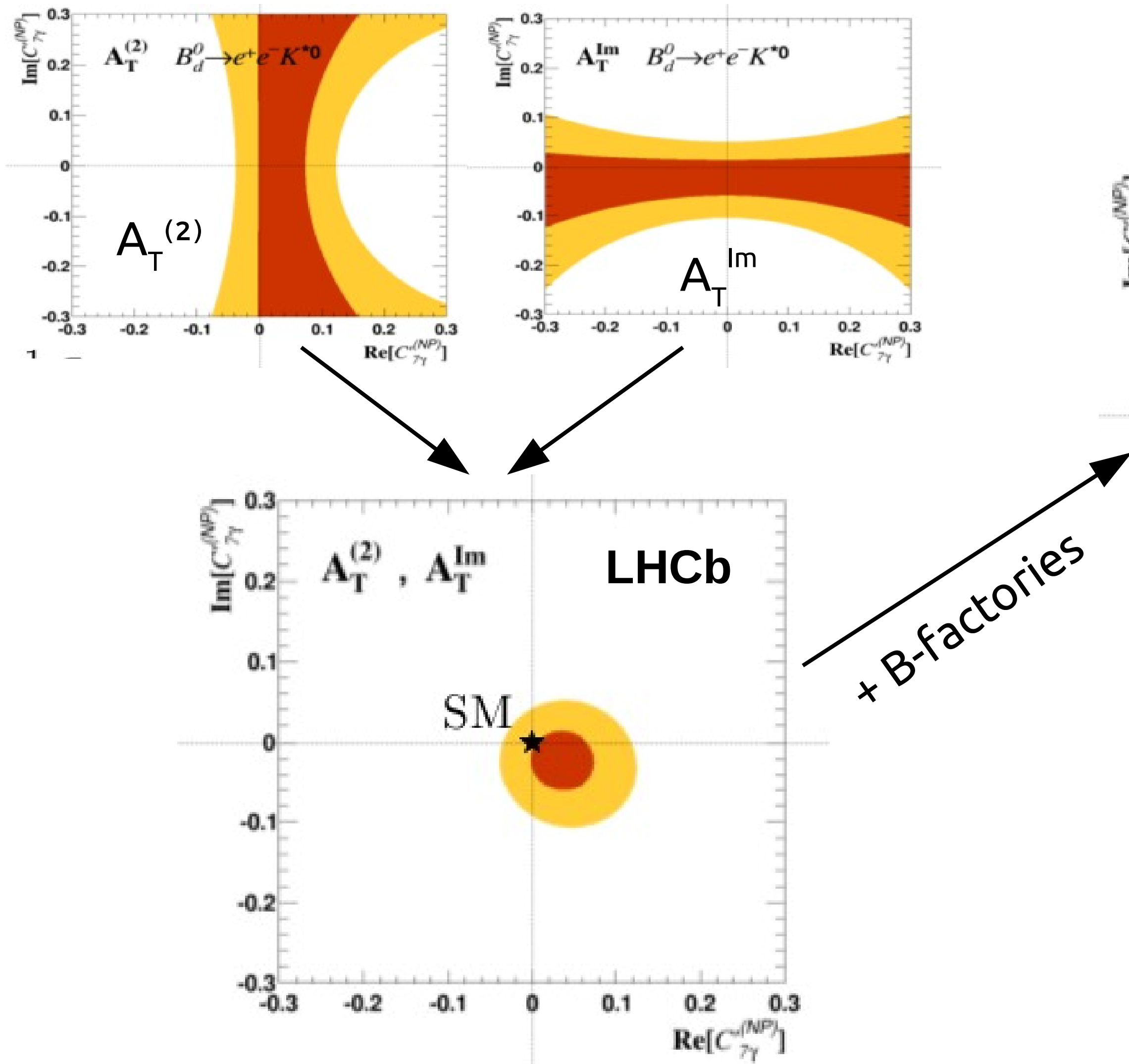
Adapted from Jäger and Camalich arXiv:1412.3183

- Consistence with SM predictions
- Uncertainties mainly **limited by statistics**

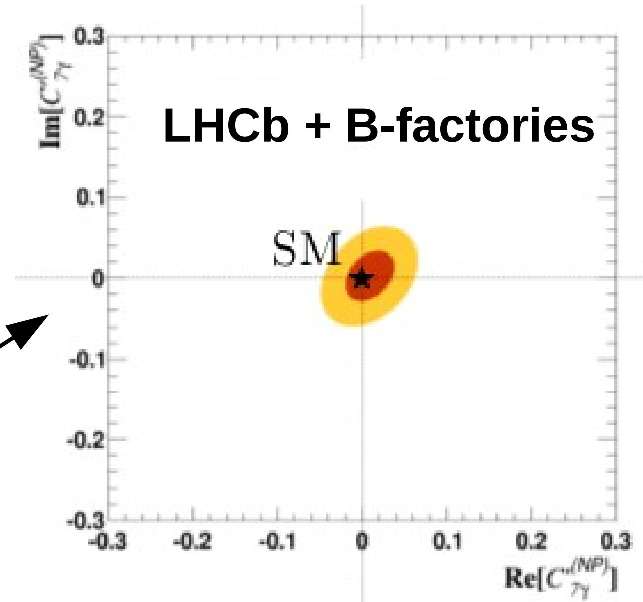
[LHCb collaboration, JHEP04(2015)064]

$B^0 \to K^{*0} e^+ e^-$

- Constraints on right-handed C_7' complex plane can be recalculated, including previous results from B-factories



Results from B-factories:
[BaBar PRD78 (2008) 071102, Belle PRD74 (2006) 111104]



Consistent with the SM

$B_s \to \phi\gamma$

- Photon polarization can be extracted also from **time-dependent decay rate** distributions in $B_{(s)} \to f_{CP}\gamma$ decays

$$\Gamma_{\overset{(-)}{B^0_s} \to \phi\gamma}(t) =$$

$$= |A|^2 e^{-\Gamma_s t}\left(\cosh\frac{\Delta\Gamma_s t}{2} - \mathcal{A}^\Delta \sinh\frac{\Delta\Gamma_s t}{2} \pm \mathcal{C}\cos\Delta m_s t \mp \mathcal{S}\sin\Delta m_s t\right)$$

~ 0 in the SM

$$\boxed{\mathcal{A}^\Delta \approx \sin 2\psi\cos\varphi_s}$$

$$\boxed{\mathcal{S} \approx \sin 2\psi\sin\varphi_s}$$ **~ 0 in the SM**

$$\tan\psi = \boxed{\frac{B \to f_{CP}\,\gamma_L}{B \to f_{CP}\,\gamma_R}},$$ Fraction of photon helicities

- $\mathcal{A}^\Delta$ and **S** are sensitive to photon polarization
- The **untagged** analysis is still sensitive to $\mathcal{A}^\Delta$

$$\Gamma_{B_s}(t) \propto |A|^2 e^{-\Gamma_s t}\left[\cosh(\Delta\Gamma_s t/2) - \boxed{\mathcal{A}^\Delta}\sinh(\Delta\Gamma_s t/2)\right].$$

- SM prediction: $\mathcal{A}^\Delta_{SM}$ **= 0.047 ± 0.025 + 0.015** **[Muheim et al., PLB664(08)174]**
- Left-Right Symmetric model: $\mathcal{A}^\Delta_{LRSM}$ **~ 0.7** **[Atwood et al., PRL79(97)185]**

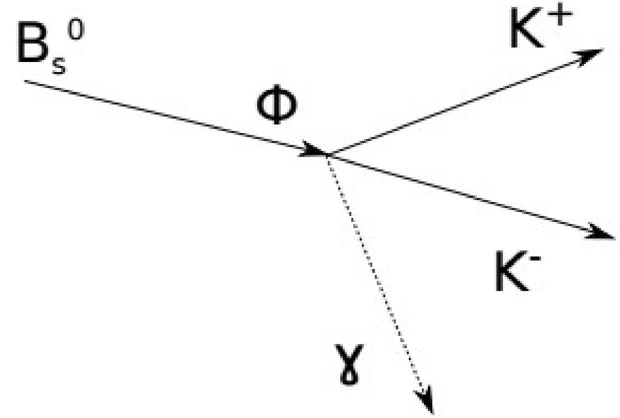
$B_s \to \phi\gamma$

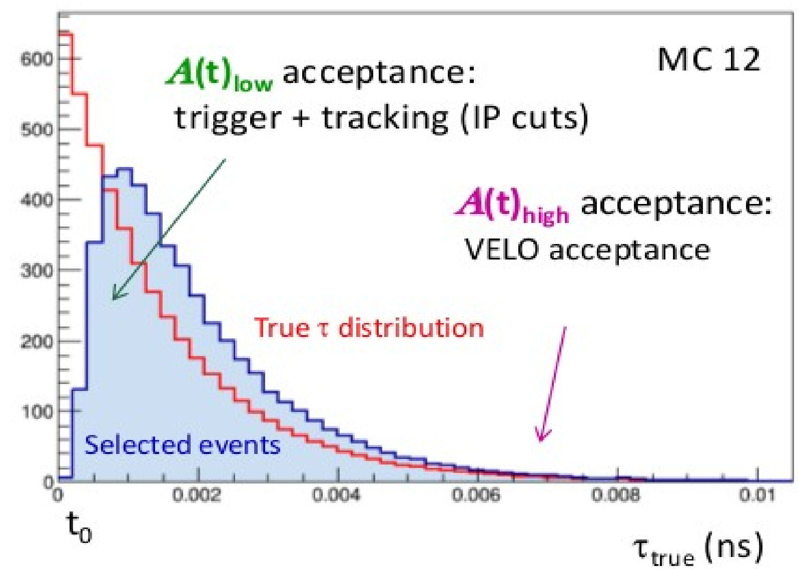
- Expected number of $B_s \to \phi\gamma$ decays:
  - Run1: ~4000 events
  - Run2: ~10000 events
- Untagged proper time distribution

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

- The reconstruction efficiency of the decay depends on the propertime
  - This **acceptance function A(t)** is one of the main concerns of the analysis
- A(t) can be extracted from the control channel $B^0 \to K^*\gamma$ and validated with simulations

$BR[B_s \to \phi\gamma] \simeq (3.6 \pm 0.4) \times 10^{-5}$



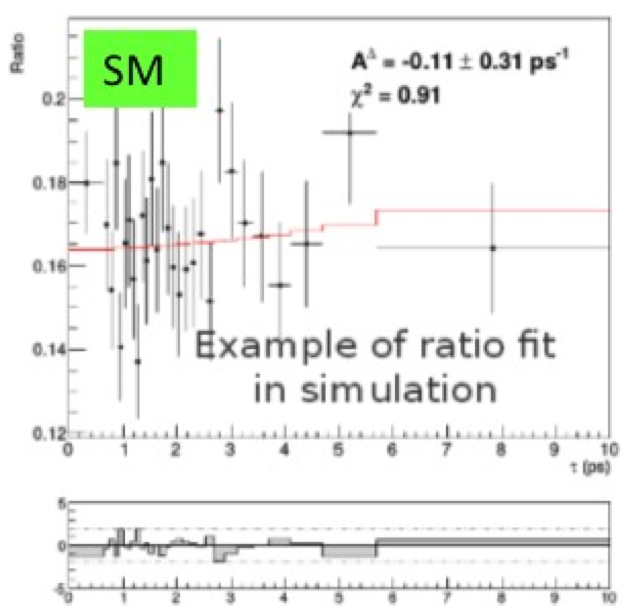


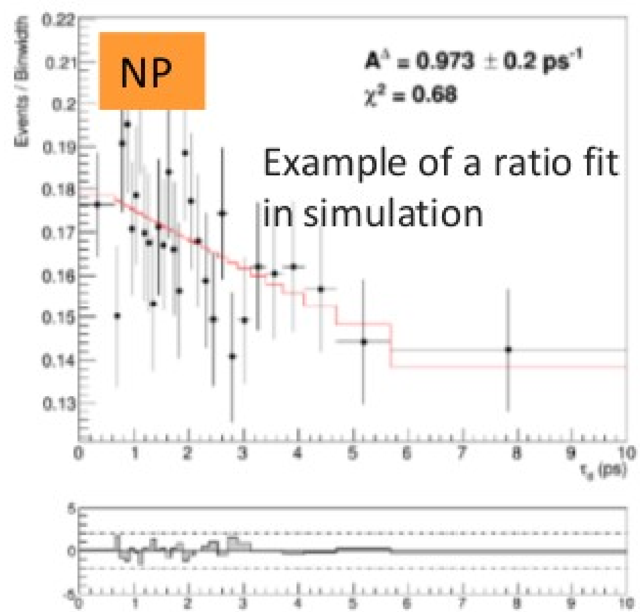
(analysis in progress...)

$B_s \to \phi\gamma$

- The ratio $B_s \to \phi\gamma$ / $B^0 \to K^*\gamma$ is sensitive to the photon polarization

$$R_i^{\mathrm{exp}}(t) = \frac{\int_{t^i_{\mathrm{low}}}^{t^i_{\mathrm{high}}} e^{-t/\tau_s} \left\{\cosh\frac{\Delta\Gamma_s t}{2} - \boxed{\mathcal{A}^{\Delta}} \sinh\frac{\Delta\Gamma_s t}{2}\right\}}{\int_{t^i_{\mathrm{low}}}^{t^i_{\mathrm{high}}} e^{-t/\tau}}. \qquad \chi^2 = \sum_i^{\mathrm{bins}} \frac{\left(R_i^{\mathrm{exp}} - R_i^{\mathrm{obs}}\right)^2}{\left(\sigma_i^{\mathrm{obs}}\right)^2},$$





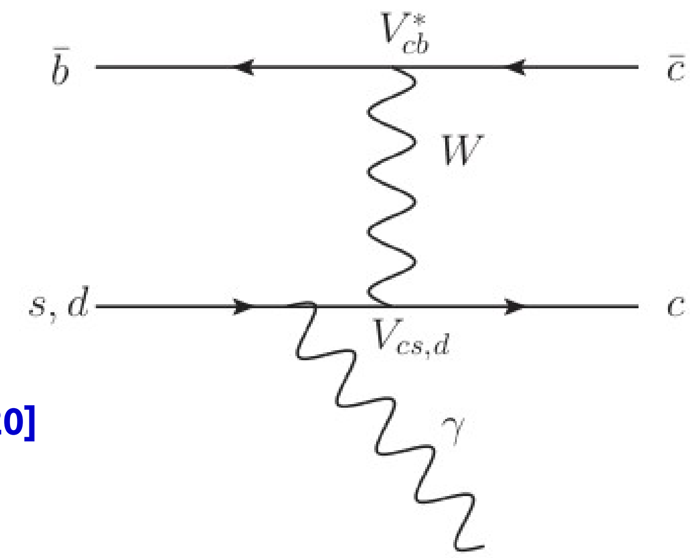
- Sensitivity limited by statistics
- Largest systematics coming from the knowledge of the acceptance

$B_{(s)} \to J/\Psi\ \gamma$

- $B_{(s)} \to J/\Psi\gamma$ decays proceed through a *W* exchange diagram, sensitive to NP particles (*e.g.* right-handed currents, charged Higgs)

- SM predictions for the BR vary significantly depending on the approach for the QCD interactions
  - $B^0 \to J/\Psi\gamma$: 7×10^{-9} 5×10^{-7}
  - $B_s \to J/\Psi\gamma$: 2×10^{-7} 5×10^{-6}

  [Yang et al, arXiv:0308256] (QCD factorization) **[Li et al, arXiv:0605220]** (perturbative QCD)



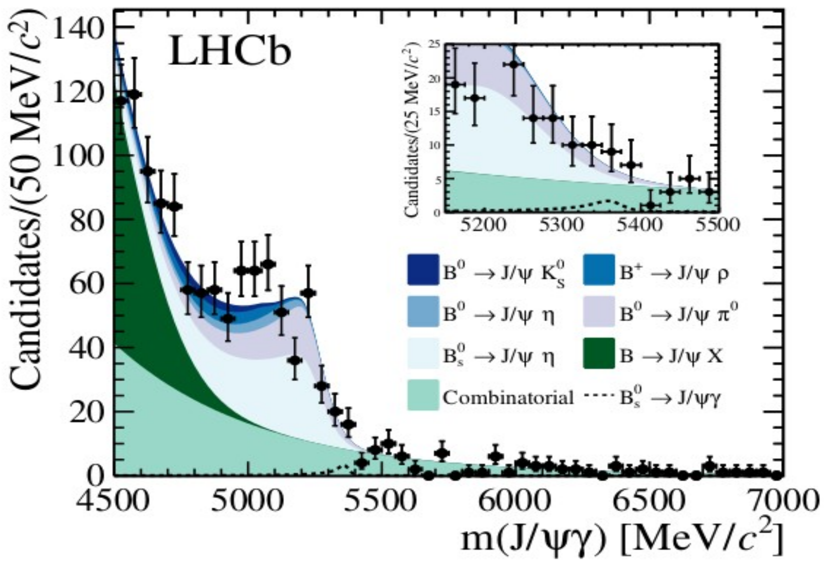
- Previous limit from BaBar
  - $BR[B^0 \to J/\Psi\gamma] < 1.6 \times 10^{-6}$ at 90% CL

  [Phys.Rev.D70:091104,2004]

[LHCb collaboration, arXiv:1510.04866]

$B_{(s)} \to J/\Psi\ \gamma$

- Only photons which **convert to e^+e^-** pairs are considered, in order to supress background from $B \to J/\Psi \pi^0$ where both photons from the π^0 are reconstructed as a single photon
- The efficiency is reduced by a factor 30, but the reconstructed mass resolution is 5 times narrower
- Split between *long* LL (full tracking) and *downstream* DD (conversion outside VELO) electron tracks
- Normalization to $B \to J/\Psi X$
  - Most systematics cancel out
- $B^0 \to K^*\gamma$ used to validate the selection and control systematics



Signal compatible with background-only hypothesis

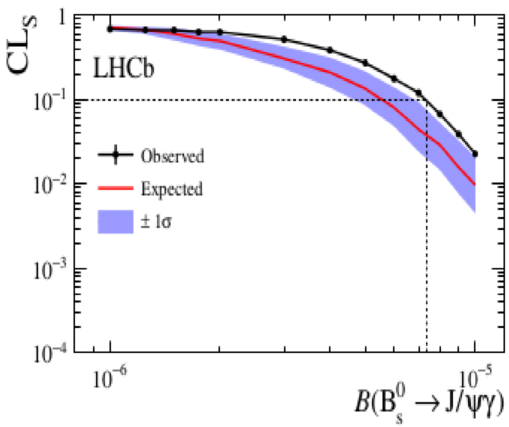
[LHCb collaboration, arXiv:1510.04866]

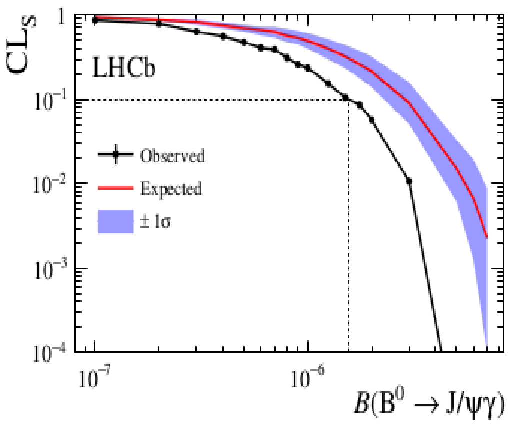
$B_{(s)} \to J/\Psi\ \gamma$

- Branching ratio CL limits

$$\mathcal{B}(B_s^0 \to J/\psi\,\gamma) < 7.4\ (8.6) \times 10^{-6} \text{ at } 90\ (95)\% \text{ CL},$$
$$\mathcal{B}(B^0 \to J/\psi\,\gamma) < 1.7\ (2.1) \times 10^{-6} \text{ at } 90\ (95)\% \text{ CL}.$$

- Observed and expected CL exclusions as function of the BR hypothesis





- $B^0 \to J/\Psi\gamma$ limit competitive and in agreement with BaBar. Two orders of magnitude higher than SM prediction
- First limit on $B_s \to J/\Psi\gamma$, close to SM prediction. Possible first observation with Run2 data

Conclusions

- We are measuring at LHCb the **photon polarization** from different channels and methods
  - $B^+ \to K^+ \pi^- \pi^+ \gamma$
  - $B^0 \to K^{*0} e^+ e^-$
- Useful to constrain $\mathbf{C_7^{(\prime)}}$ in SM extensions
- Constraints already more precise than in B-factories
- Other channels in progress: $B_s \to \phi\gamma$