Rare B decays at LHCb

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on behalf of the LHCb collaboration

Instituto de Fisica Corpuscular (IFIC, UV-CSIC)

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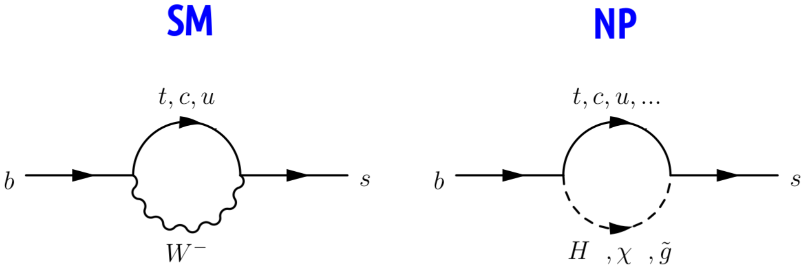
Outline

1. Introduction: Rare decays
2. Latest results on Rare Decays
   - Very Rare Decays (see Marco Santamaria's and Anna Lupato's talk)
   - Electro-weak decays (see Vitalii Lisovskyi's talk)
   - Radiative Decays
3. Conclusions

Introduction

Flavour Changing Neutral Currents (FCNC) are forbidden in Standard Model (SM) at tree level:

- Supressed (Rare processes)
- Potential interences from NP diagrams
- NP contributions could significantly change the value of observables
- This talk focus on FCNC in b-decays: $b \to s(d)$



Introduction

Model independent description by EFT: Operator product expansion.

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left-handed part}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right-handed part}}]$$

i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

- W^- bosons only couple to left-handed quarks $\implies$ right-handed currents suppressed
- Wilson Coefficients ($\mathcal{C}_i$) parametrize coupling strength and describe loop part of the diagrams
- Looking for deviation w.r.t SM prediction:

$$\begin{cases} \mathcal{C}_i = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP} \\ \mathcal{C}'_i = \mathcal{C}_i'^{NP} \end{cases}$$

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suppressed in SM

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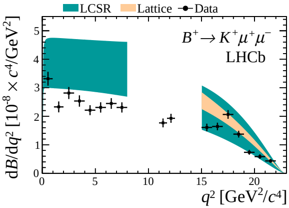
Experimental status

Tensions w.r.t SM in several decay channels with a $b \to sll$ transition from:

- Branching ratios
- Angular observables
- Lepton Flavour Universality tests (see Marco Santimaria's talk)

JHEP06(14)133



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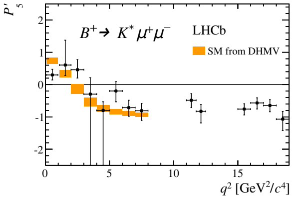

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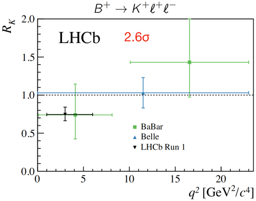
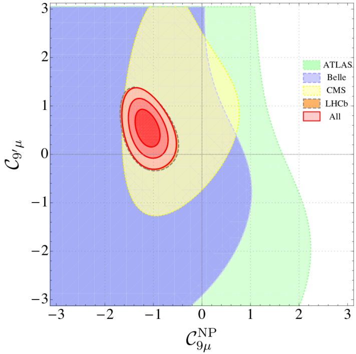
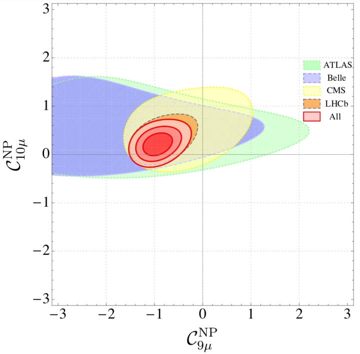


- Large theory uncertainty in branching ratios due to form factors

Experimental status

Global fits show possible NP contributions in C_9 or both C_9 and C_{10} [M.Alguero et al, arXiv:1903.09578]:



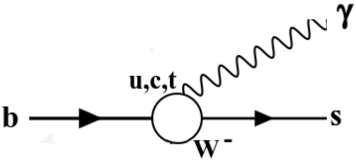


- Several models including Leptoquarks and Z' have arisen to explain these deviations

Radiative decays

- Rare decays with a $b \to s\gamma$ transition
- Mostly sensitive to C_7 and C_7' through photon polarization:

$$\boldsymbol{\alpha}_\gamma = \frac{P(\gamma_L) - P(\gamma_R)}{P(\gamma_L) + P(\gamma_R)} \qquad \boldsymbol{\alpha}_\gamma{}^{LO} = \frac{|C_7|^2 - |C_7'|^2}{|C_7|^2 + |C_7'|^2}$$



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

Time-dependent decay rates of $B_s \to \phi\gamma$ and $\overline{B_s} \to \phi\gamma$ grant access to photon polarization:

$$\Gamma_{B_s\to\phi\gamma}(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \mathcal{A}^{\Delta}_{\phi\gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_{\phi\gamma}\cos(\Delta m_s t) - S_{\phi\gamma}\sin(\Delta m_s t)\right]$$

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- $\mathcal{A}^{\Delta}_{\phi\gamma}$ and $S_{\phi\gamma}$ are sensitive to photon polarization
- $C_{\phi\gamma}$ is related to direct CP violation
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*Untag: No separation between B_s and $\overline{B_s}$

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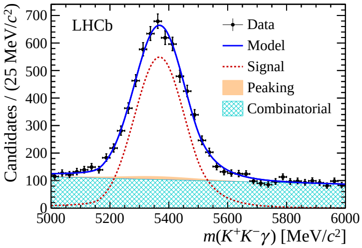
- **New:** $S_{\phi\gamma}$ and $C_{\phi\gamma}$ measurement using flavour tagging

*Tagging: Separation between B_s and $\overline{B_s}$ [JINST11(2016)P05010]

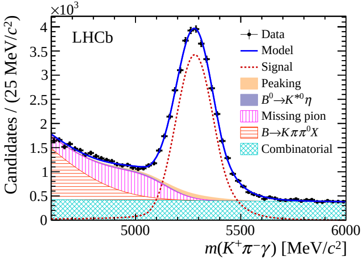
- Mass fit of $B_s \to \phi\gamma$ (signal) and $B \to K^*\gamma$ (control) decays
- Using Run 1 data at LHCb [LHCb: arXiv:1905.06284]
- Background subtracted with sPlot technique, fitting the B mass
  - Signal: Double-side Crystal Ball
  - Combinatorial: First order polynomial
  - Partially reconstructed: ARGUS convoluted with a Gaussian

Signal: $B_s \to \phi\gamma$



5300 signal yield

Control: $B \to K^*\gamma$



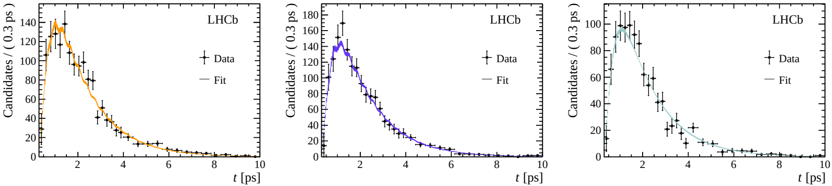
32000 signal yield

Time-dependent analysis of $B_s \to \phi\gamma$: Proper time fit

Analysis strategy:

- Simultaneous unbinned ML fit to $B_s \to \phi\gamma$ (signal) and $B_s \to K^*\gamma$ (control) channels
- Mis-tag probability and resolution evaluated per event

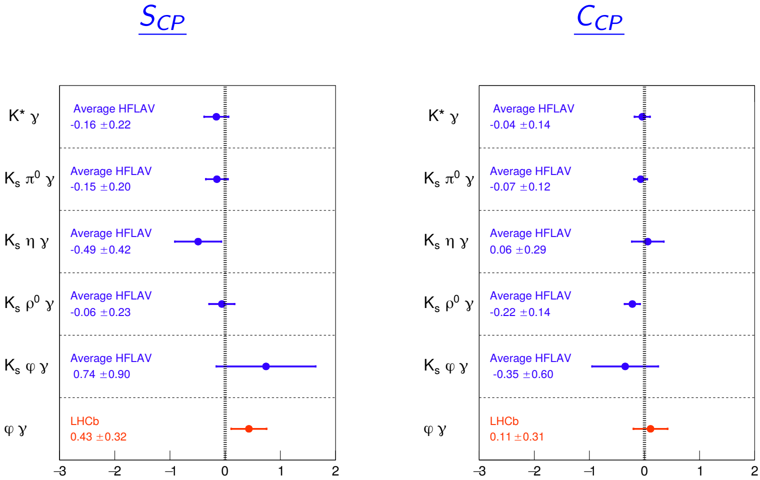
Tag: B_s | Tag: $\overline{B_s}$ | Untag



$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11,$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11,$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$

- Compatible with SM at 1.3, 0.3, 1.7 σ
- First measurement of S and C in the $B_s \to \phi\gamma$ decay [LHCb: arXiv:1905.06284]

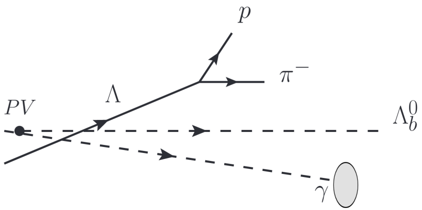
S_{CP} and C_{CP} in $b \to s\gamma$ transitions



- Measurement competitive with other results from b-factories

Search for $\Lambda_b^0 \to \Lambda^0\gamma$ decay

- Recontruction is very challenging: no Λ_b^0 vertex
  - No direction from γ cluster
  - Λ is a long-lived particle (LLP) $\Longrightarrow$ Λ_b^0 vertex $\neq$ Λ vertex



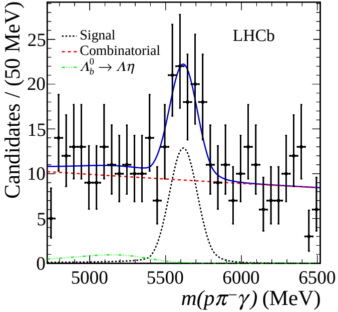
- SM prediction: $\mathcal{B}(\Lambda_b^0 \to \Lambda^0\gamma) = 10^{-7} - 10^{-5}$

Search for $\Lambda_b^0 \to \Lambda^0\gamma$ decay

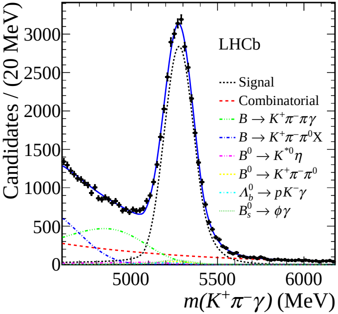
First observation of $\Lambda_b^0 \to \Lambda^0\gamma$ using 2016 data (1.7 fb^{-1})
[LHCb: arXiv:1904.06697]

- Signal excess of $5.6\,\sigma$ significance

Signal: $\Lambda_b^0 \to \Lambda^0\gamma$



Control: $B \to K^*\gamma$



$$\mathcal{B}(\Lambda_b^0 \to \Lambda^0\gamma) = (7.1 \pm 1.5_{stat} \pm 0.7_{syst} \pm 0.6_{f_{\Lambda_b^0}/f_{B^0}}) \times 10^{-6}$$

Photon polarization in $\Lambda_b^0 \to \Lambda^0\gamma$

The $\Lambda_b^0 \to \Lambda^0\gamma$ observation opens the possibility for direct measurement of photon polarization (α_γ) in b-baryon decays [arXiv:1902.04870]:

$$\Gamma_{\Lambda_b}(\theta_\gamma, \theta_p) = 1 - \alpha_\Lambda P_{\Lambda_b} \cos\theta_p \cos\theta_\gamma - \boldsymbol{\alpha_\gamma}\left(\alpha_\Lambda \cos\theta_p - P_{\Lambda_b}\cos\theta_\gamma\right)$$

Integrating in helicity angles:

$$\Gamma_{\Lambda_b}(\theta_\gamma) = \frac{1}{4}\left(1 - \boldsymbol{\alpha_\gamma} P_{\Lambda_b}\cos\theta_\gamma\right)$$

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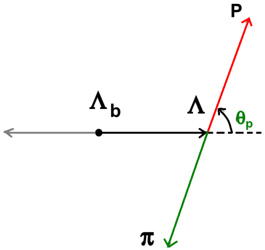

The decay parameters are:

- $P_{\Lambda_b} = 0.00 \pm 0.06(stat) \pm 0.06(sys)$ [CMS: PRD97(2018)072010]
- $\alpha_\Lambda = 0.642 \pm 0.013$ [PDG 2018]

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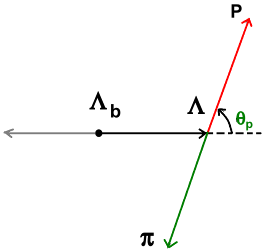

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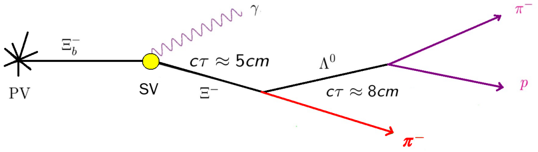
Other remarkable channels: $\Xi_b^- \to \Xi^- \gamma$

The $\Xi_b^- \to \Xi^- \gamma$ decay is also sensitive to photon polarization through angular distribution [arXiv:1902.04870]:

- Two long-lived particle involved
- Extra decay
- Additional helicity angle



$$\Gamma_{\Xi_b^-}(\theta_\Xi, \theta_\Lambda, \theta_p) \propto 1 + \alpha_\Lambda \alpha_\Xi \cos\theta_p - \alpha_\gamma \alpha_\Xi \cos\theta_\Lambda - \alpha_\gamma \alpha_\Lambda \cos\theta_\Lambda \cos\theta_p$$
$$- P_{\Xi_b} \alpha_\Xi \cos\theta_\Xi \cos\theta_\Lambda + P_{\Xi_b} \alpha_\gamma \alpha_\Xi \alpha_\Lambda \cos\theta_\Xi \cos\theta_p$$
$$- P_{\Xi_b} \alpha_\Lambda \cos\theta_\Xi \cos\theta_\Lambda \cos\theta_p + P_{\Xi_b} \alpha_\gamma \cos\theta_\Xi$$

The values of the decay parameters are:

- $\alpha_\Xi = -0.458 \pm 0.012$ [PDG 2018]
- $\alpha_\Lambda = 0.642 \pm 0.013$ [PDG 2018]

Other remarkable channels: $\Xi_b^- \to \Xi^-\gamma$

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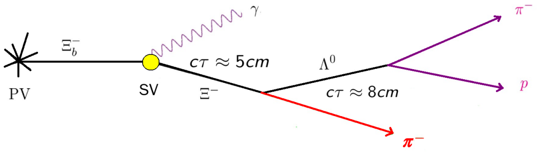

$$\Gamma_{\Xi_b}(\theta_\Lambda, \theta_p) = \frac{1}{4}\left(1 - \boldsymbol{\alpha_\gamma}\alpha_\Xi \cos\theta_\Lambda + \alpha_\Lambda \cos\theta_p \left(\alpha_\Xi - \boldsymbol{\alpha_\gamma} \cos\theta_\Lambda\right)\right)$$

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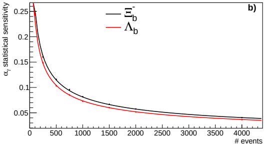
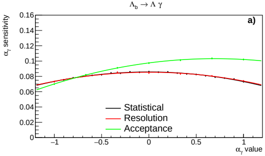
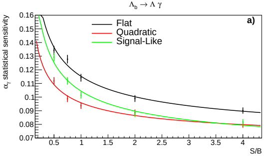
Sensitivity to the photon polarization in b-baryon decays using angular distribution [arXiv:1902.04870]:

Statistical	Resolution + Acceptance	Background

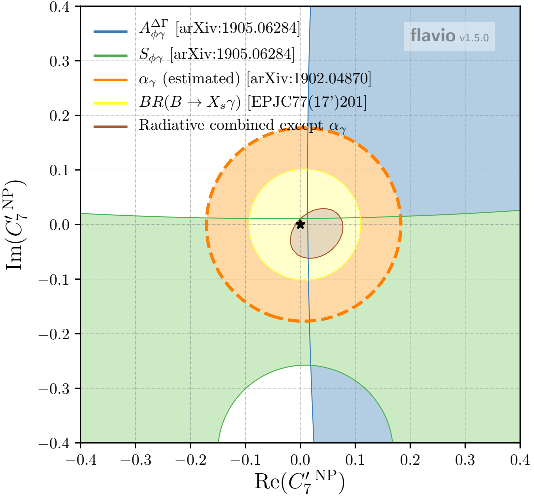






- Statistical uncertainty: Goes as $1/\sqrt{N}$ with number of events
- Resolution: Effect neglible
- Acceptance: Asymmetric in α_γ
- Background: Important dilution. Low dependence with the shape

NP Constraints



[arXiv:1810.08132]

Observables in the $b \to s\gamma$ transition:

- Branching ratios
- $\mathcal{A}^{\Delta}_{\phi\gamma}$ and $S_{\phi\gamma}$
- Angular observables

give complementary constraints in the $\mathcal{C}_7'$ complex plane

Conclusions

Experimental status:

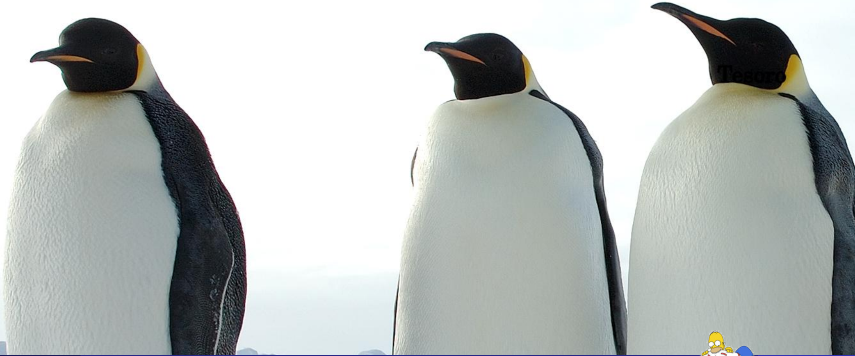
- Rare decays are excellent probes of NP
- They are extensively studied at LHCb
- Multiple tension w.r.t. SM in $b \to sll$ transitions
- Rare c-decays are also heavily studied (see Dominik Mitzel's talk)

Latest results from LHCb:

- First measurements of $C_{\phi\gamma}$ and $S_{\phi\gamma}$ in B_s decays
- First observation of $\Lambda_b^0 \to \Lambda^0\gamma$
    - First step toward the direct measurement of the photon polarization

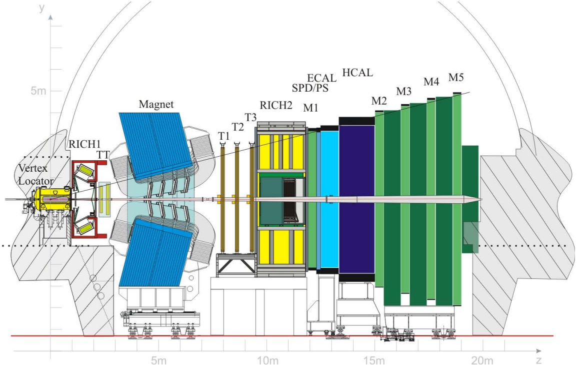
Many more results with Run 2 data ongoing

Thanks for your attention

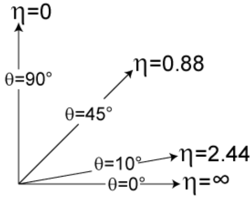


LHCb detector

- One of the four detector at LHC
- LHCb is a single-arm $(2 < \eta < 5)$ spectrometer



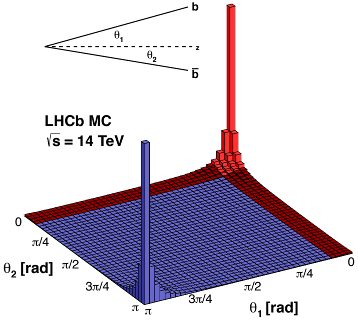
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

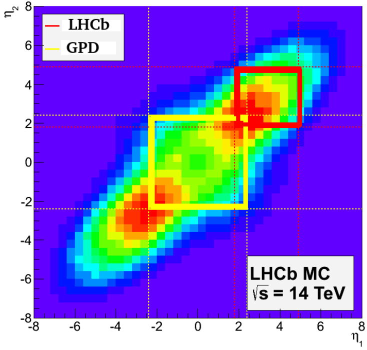


θ: Angle between **p** and positive beam axis.

LHCb detector

- One of the four detector at LHC
- LHCb is a single-arm ($2 < \eta < 5$) spectrometer
- Optimised for beauty and charm decays



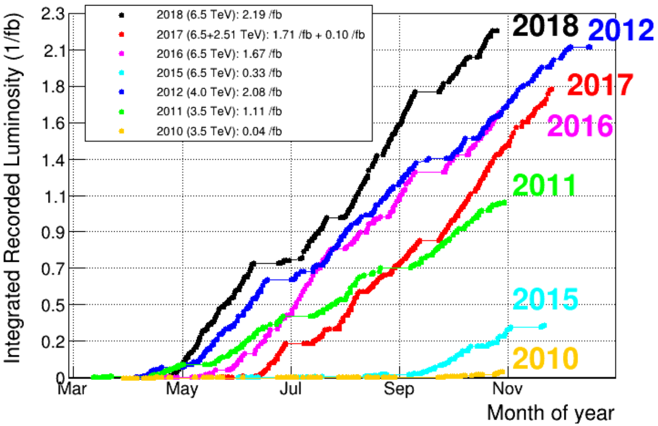


LHCb Detector

Expected integrated Luminosity:

- Run II (2018): $6fb^{-1}$

$1\ \text{fb}^{-1} \approx 10^{12}$ pp collisions



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

Main systematics:

	Uncertainty source	$\sigma(\mathcal{A}^{\Delta})$	$\sigma(S)$	$\sigma(C)$
Statistical	Fit outcome	$^{+0.347}_{-0.379}$	0.264	0.250
External measurements	$(\Gamma_s, \Delta\Gamma_s)$	0.086	0	0
	Γ_d	0.043	0	0
	Δm_s	0	0.008	0.013
Decay time	Acceptance: MC limited statistics	0.082	0	0
	Acceptance: modelling	0.028	0	0
	Resolution: MC limited statistics	0	0.001	0.002
	Resolution: modelling	0	0.096	0.075
Toy studies	Limited statistics	0.011	0.011	0.011
Mistag probability	OS tagger calibration	0	0.010	0.010
	SS tagger calibration	0	0.049	0.031
Background subtraction	Mass modelling: signal	< 0.01	< 0.01	< 0.01
	Mass modelling: combinatorial	0.034	< 0.01	< 0.01
	Mass modelling: partial	0.081	0.010	0.020
	Peaking backgrounds	0.036	0.018	0.030
	Mass-time correlation	0.110	< 0.01	< 0.01
Total	$\sigma_{\text{stat.}}$	$^{+0.347}_{-0.379}$	0.264	0.250
	$\sigma_{\text{ext.}}$	0.096	0.008	0.013
	$\sigma_{\text{syst.}}$	0.170	0.111	0.109

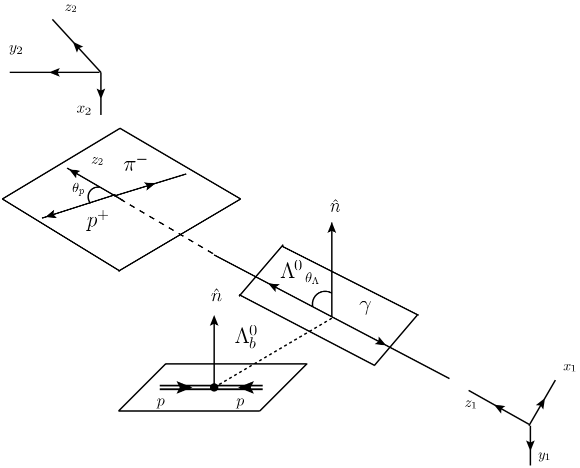
Search for $\Lambda_b^0 \to \Lambda^0 \gamma$ decay

Analysis statistically limited. Main systematics:

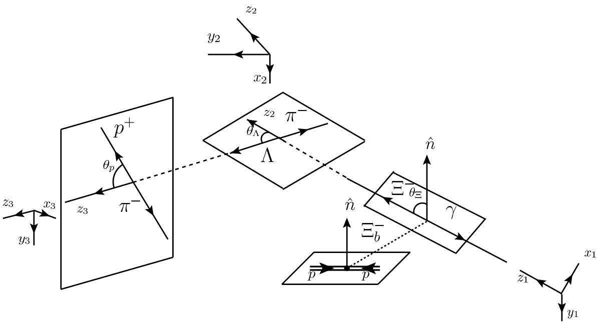
Source	Uncertainty (%)
Data/simulation agreement	7.7
Λ_b^0 fit model	3.0
$B^0 \to K^{*0}\gamma$ backgrounds	2.7
Size of simulated samples	1.7
Efficiency ratio	0.7
Sum in quadrature	8.9
$f_{\Lambda_b^0}/f_{B^0}$	8.7
Input branching fractions	3.0
Sum in quadrature	9.2

from external measurements

Helicity angles for $\Lambda_b^0 \to \Lambda^0\gamma$ decay

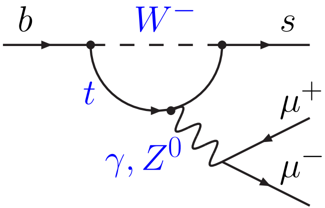


Helicity angles for $\Xi_b^- \to \Xi^- \gamma$ decay



Very Rare Decays

- Very suppressed or forbidden in the SM
- Branching ratios $\mathcal{O}(10^{-8})$ or lower
- Sensitive to C_S , C_P , C_{10} or completely new contributions



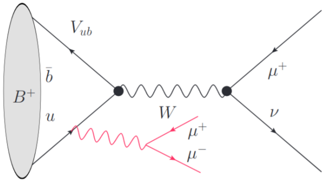
For $B \to \mu\tau$ analysis see Marco Santamaria's talk

Search for the very rare decay $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$

- Very supressed decay with $BR \propto |V_{ub}|^2$
- Using Run 1 + 2016 data (4.7 fb^{-1})
- ν_μ not detected, using corrected mass:

$$M_{corr} = \sqrt{M^2_{\mu\mu\mu} + p'^2_T} + p'_T$$

p'_T: missing momentum transverse to B^+ flight direction



- Veto charmonium resonances and selects the region $M^{min}_{\mu\mu} < 980$ MeV$/c^2$
- Normalization channel: $B^+ \to J/\psi K^+$
- Only theoretical estimation: $BR \sim 1.3 \times 10^{-7}$ [PAN (2018) 81:347]

No signal is found, a limit is set

$\mathcal{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) < 1.6 \times 10^{-8}$ (95% CL) [LHCb: arXiv:1812.06004]

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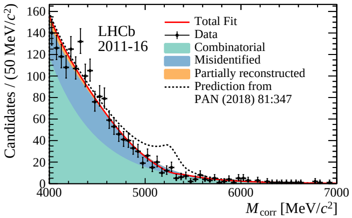

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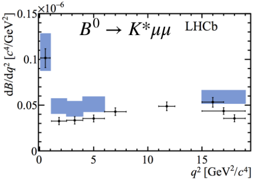
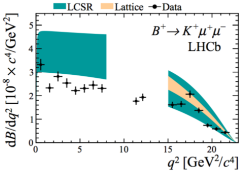
Experimental status

Deviations in several decay channels with a $b \to s(d)ll$ transition (see ???'s talk):

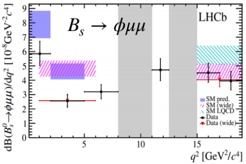
JHEP 11 (2016) 047



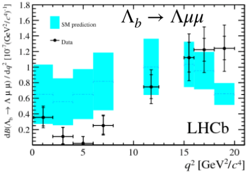
JHEP 06 (2014) 133



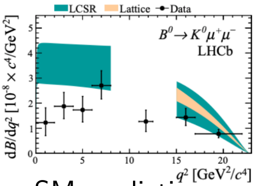
JHEP 09 (2015) 179



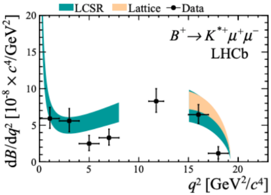
JHEP 06 (2015) 115



JHEP 06 (2014) 133



JHEP 06 (2014) 133



- Data consistently below SM predictions
- Large theory uncertainty due to form factors