中国科学院大学

University of Chinese Academy of Sciences

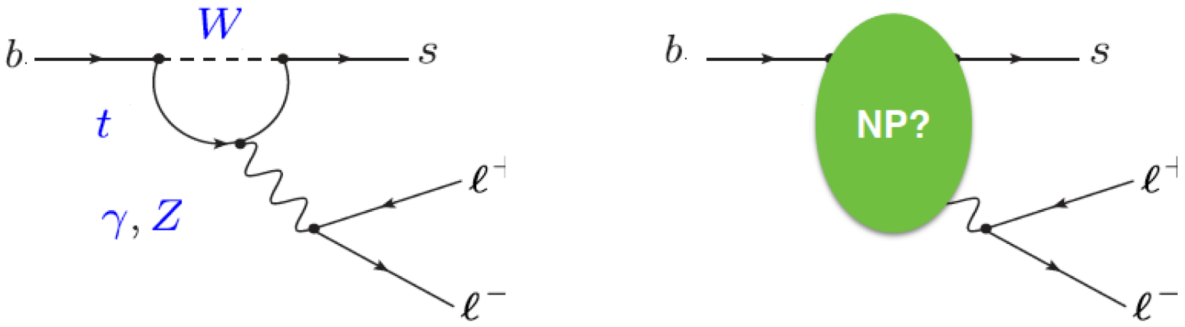
Rare *B* decays at LHCb

Jibo HE/何吉波(UCAS)

HFCPV2019 @ 内蒙古大学

Introduction

- Flavor-Changing Neutral Current (FCNC) process suppressed in SM. New Physics?



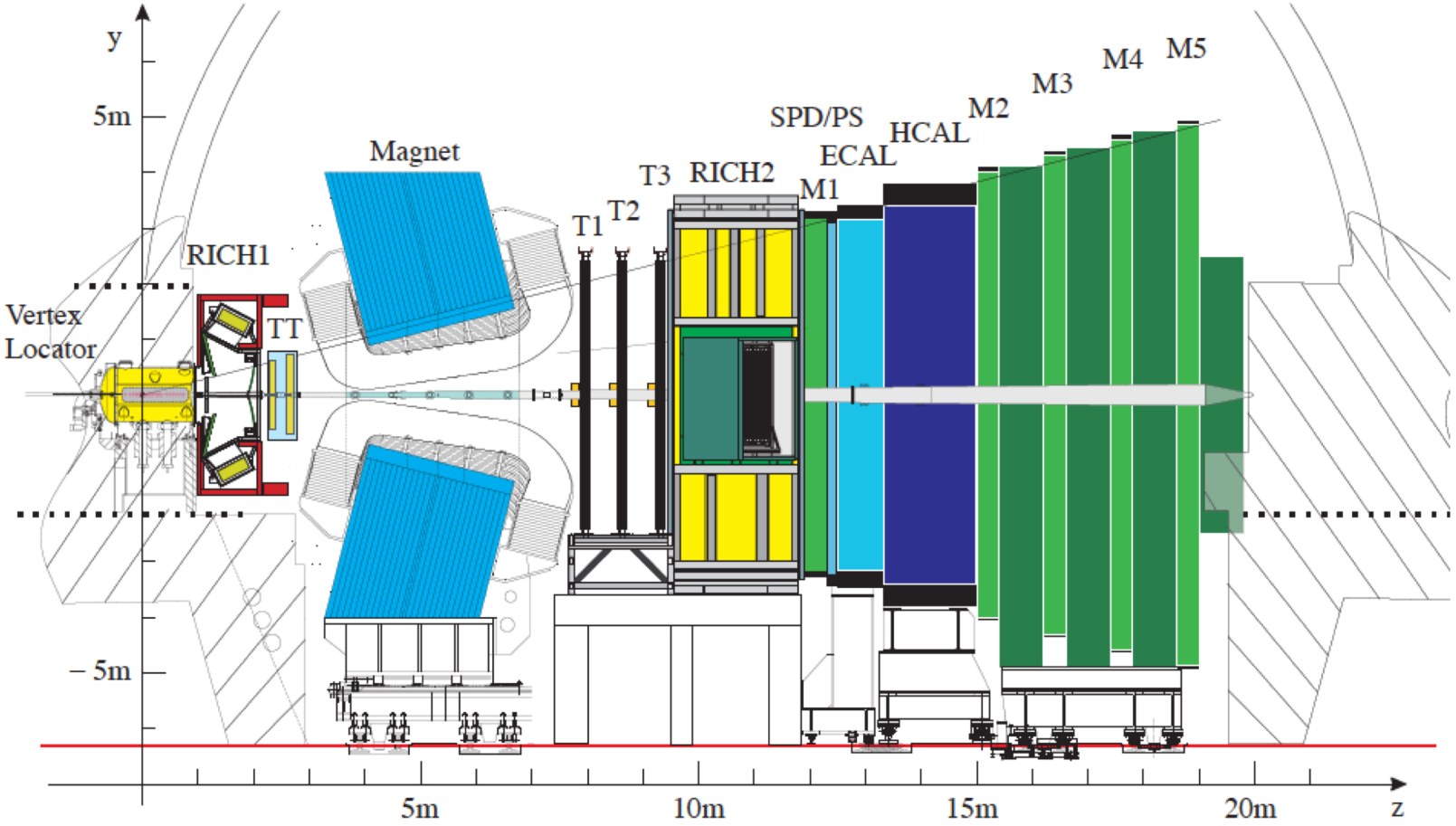
- Described by effective Hamiltonion

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

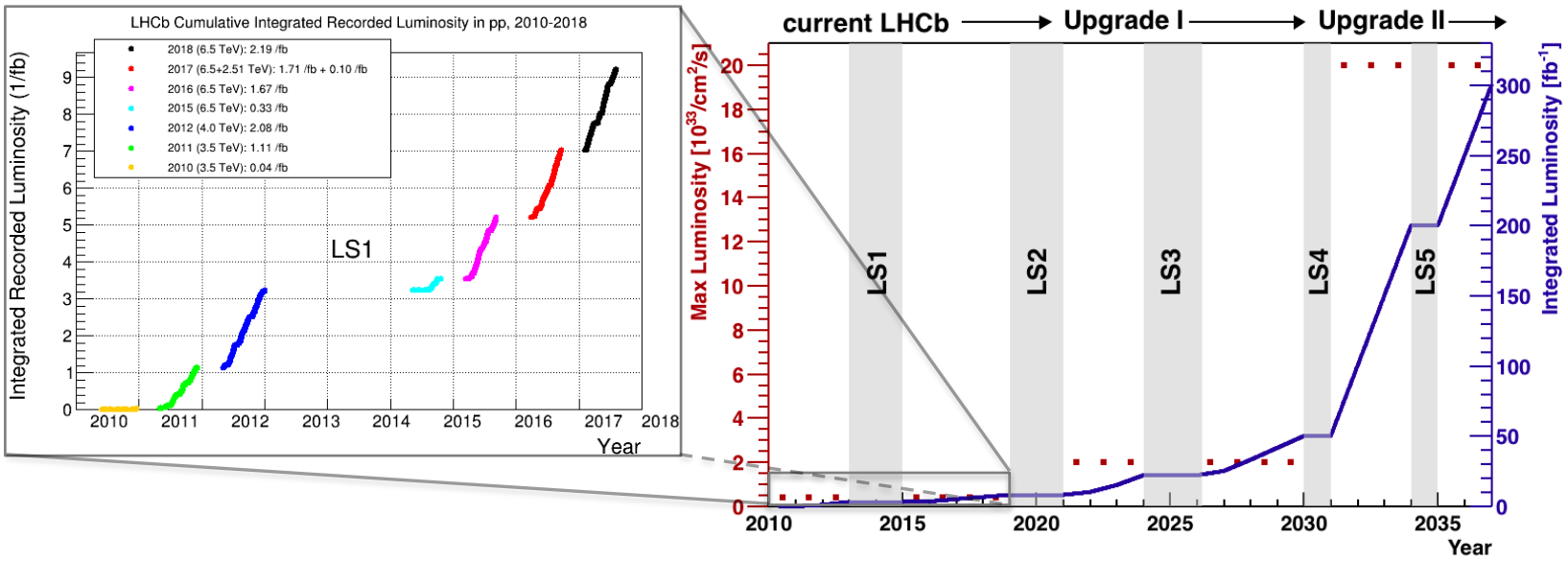
i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

The LHCb experiment

- Dedicated to precision study of *b/c*-hadrons

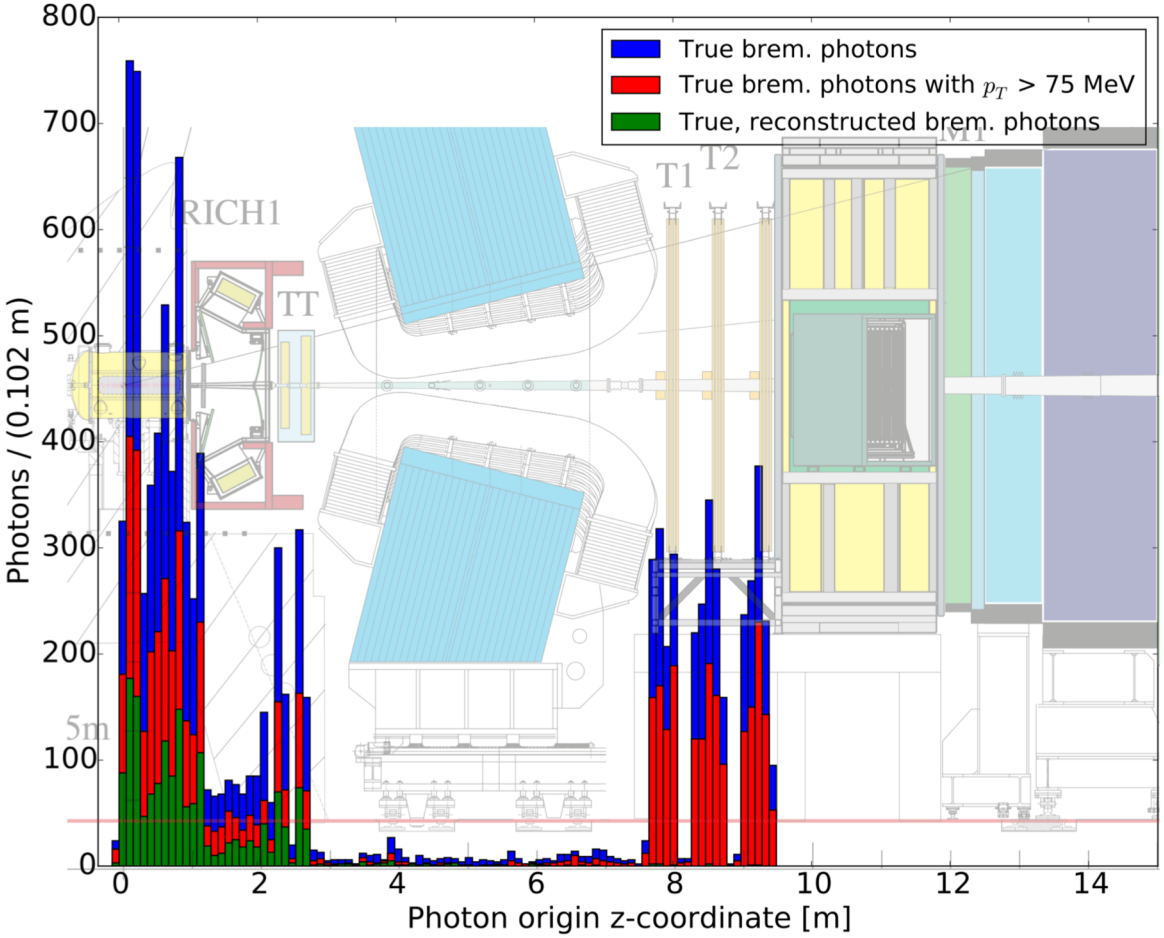


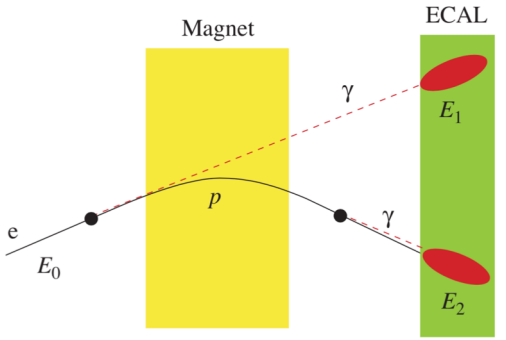
LHCb luminosity prospects

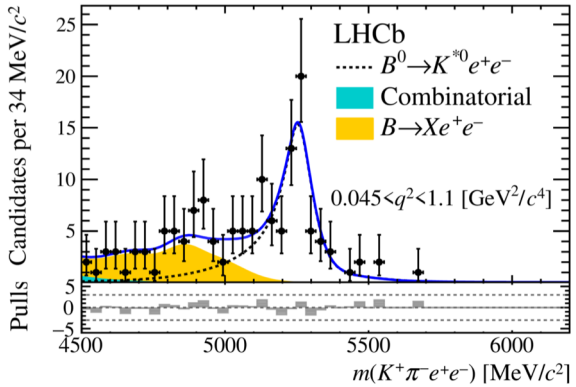


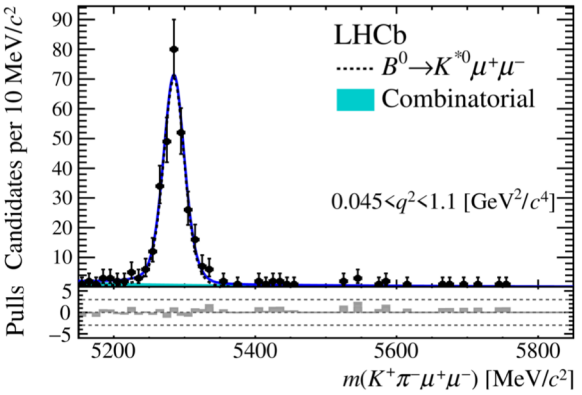
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

Bremsstrahlung corrections







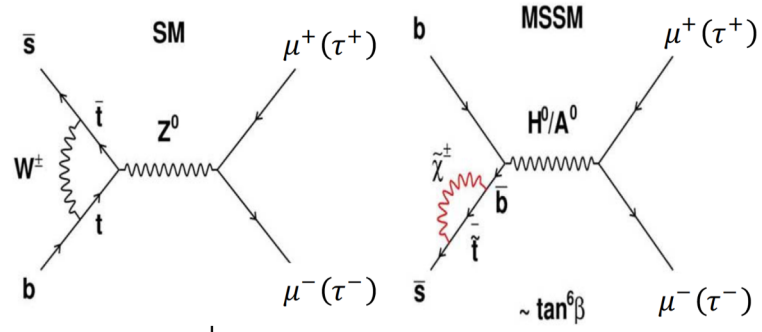


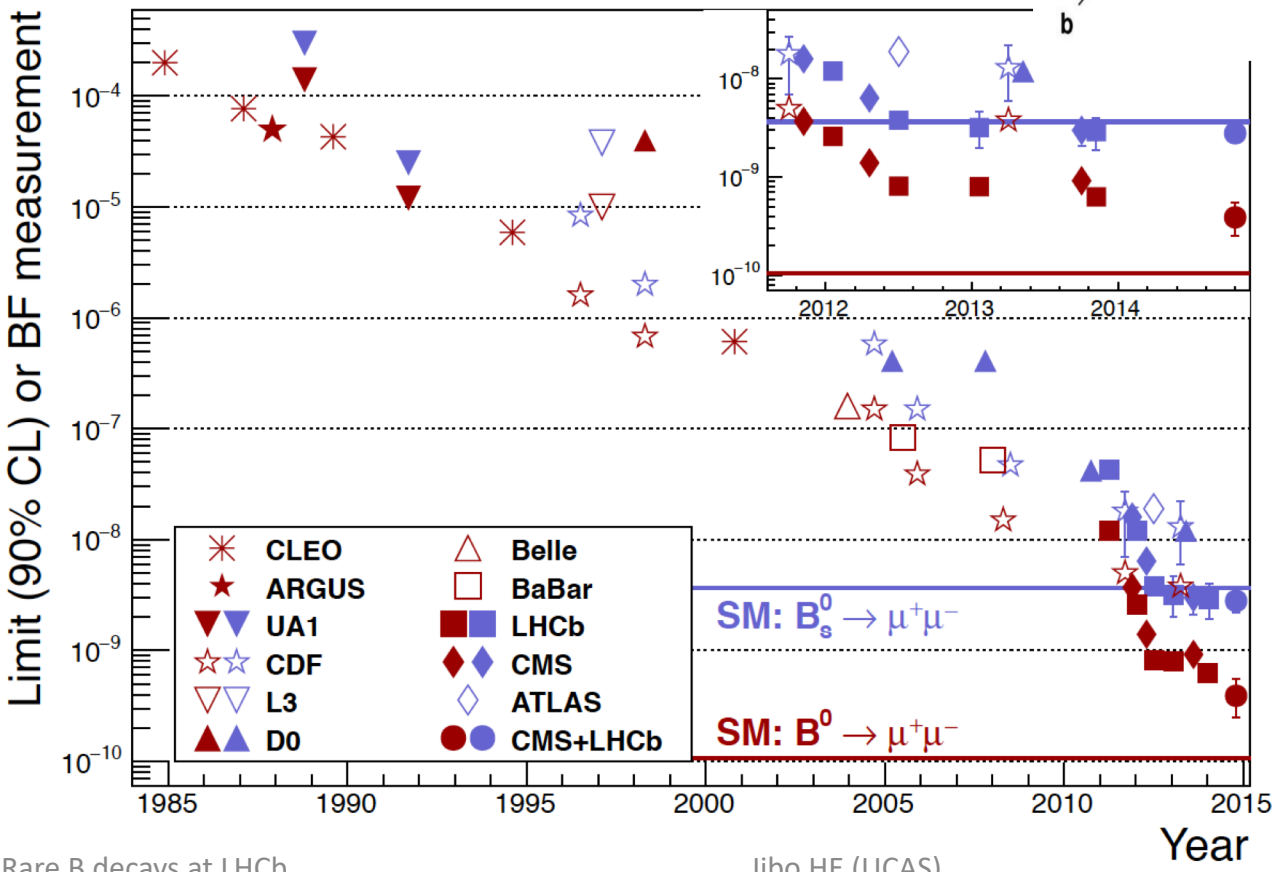
Rare decays at LHCb

- Very rare decays
  - $B^0_{(s)} \to \mu^+\mu^-, B^0_{(s)} \to \tau^+\tau^-, B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$
- Lepton flavor violation
  - $B^0_{(s)} \to \tau^+\mu^-$, $B^0_{(s)} \to e^+\mu^-, \tau^+ \to \mu^+\mu^-\mu^+$
- Electroweak penguin
  - $B^0 \to K^{*0}\mu^+\mu^-$, LFU
- Radiative
  - $B^0_s \to \phi\gamma, \Lambda^0_b \to \Lambda\gamma, B^+ \to K^+\pi^+\pi^-\gamma$
- Rare charm
  - $D^0 \to \mu^+\mu^-, \Lambda^+_c \to p\mu^+\mu^-$
- Rare Strange
  - $K^0_S \to \mu^+\mu^-, \Sigma^+ \to p\mu^+\mu^-$

$B^0_{(s)} \to \mu^+\mu^-$

- Road to $B^0_{(s)} \to \mu^+\mu^-$

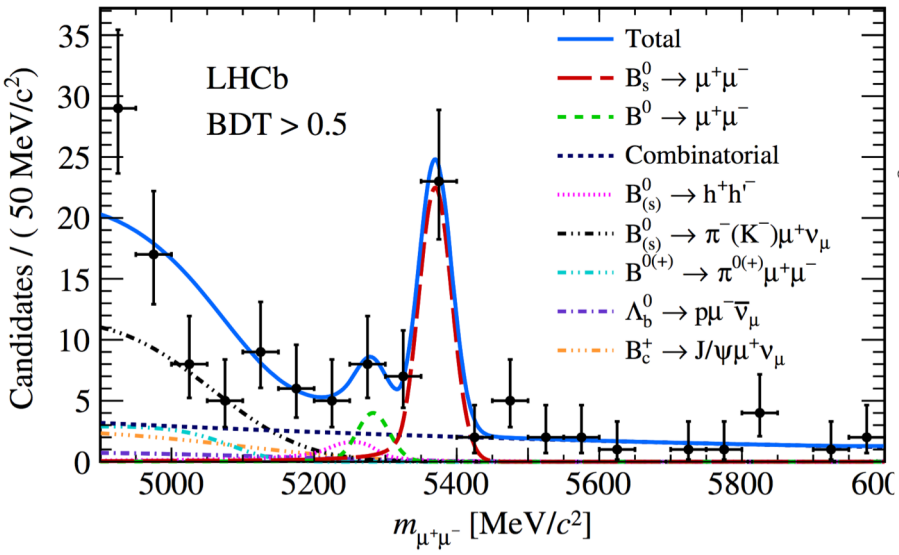


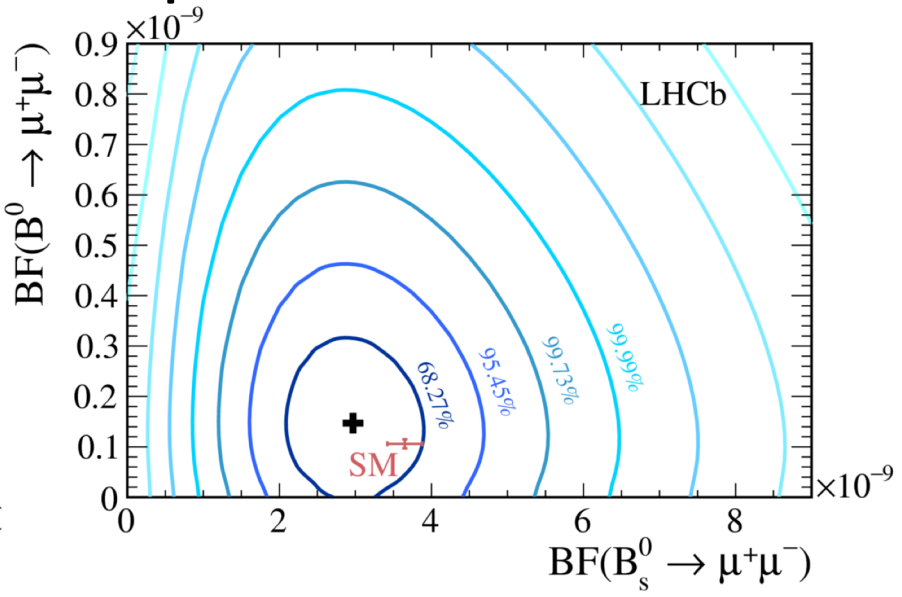


$B^0_{(s)} \to \mu^+\mu^-$, latest results from LHCb

- With 4.6 fb^{-1} of data, first observation of $B^0_s \to \mu^+\mu^-$ from a single experiment

[PRL 118 (2017) 191801]





$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$ 7.8σ LHCb alone

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \cdot 10^{-10} \text{ @ } 95\% \text{ CL}$$

$B_s^0 \to \mu^+\mu^-$ effective lifetime

- B_s^0 mixing ⇒ effective τ

$$\tau_{\mu\mu} = \frac{\tau_{B_S}}{(1-y_s^2)} \frac{1+2y_s A_{\Delta\Gamma}+y_s^2}{1+y_s A_{\Delta\Gamma}}$$

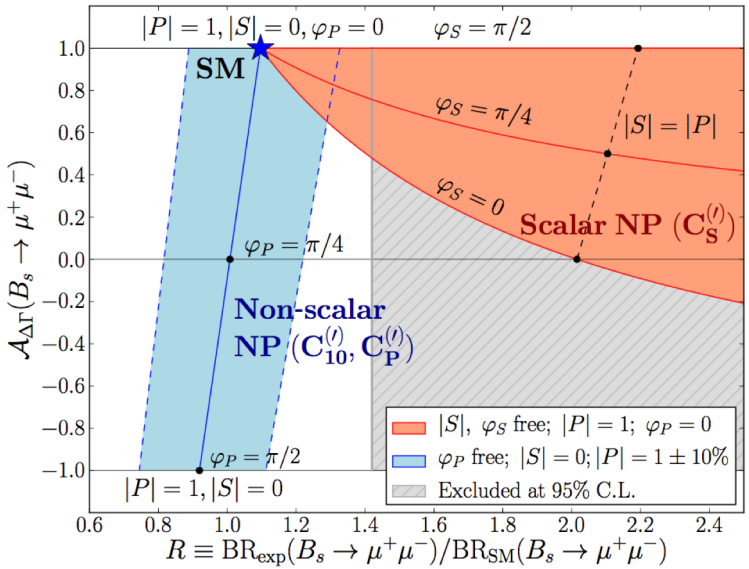
$A_{\Delta\Gamma}$=1 in SM

$$y_s \equiv \tau_{B_s} \Delta\Gamma_s/2$$

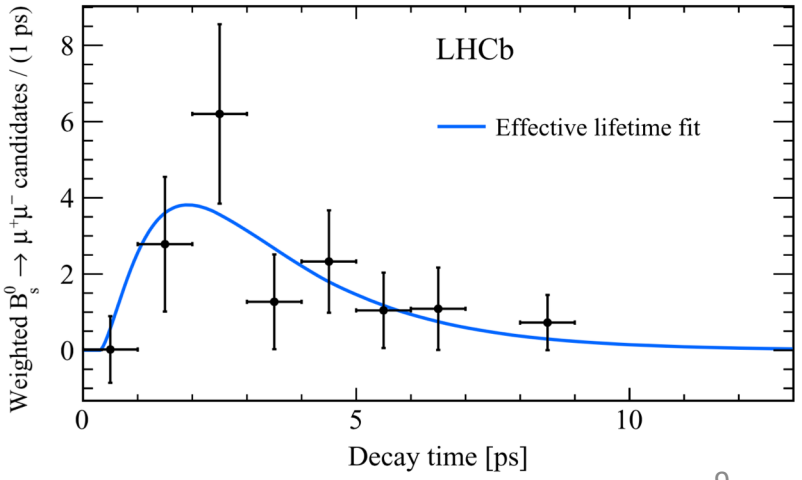
- First measurement, not yet sensitive to $A_{\Delta\Gamma}$

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

[PRL 118 (2017) 191801]



[De Bruyn *et. al.*, PRL 109 (2012) 041801]



$B^0_{(s)} \to \tau^+\tau^-$

- $B^0_{(s)} \to \tau^+\tau^-$ not helicity suppressed in SM, predicted BR ~200 higher than $B^0_{(s)} \to \mu^+\mu^-$

$$\mathcal{B}(B^0_s \to \tau^+\tau^-)_{SM} = (7.73 \pm 0.49) \times 10^{-7}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-)_{SM} = (2.22 \pm 0.19) \times 10^{-8}$$

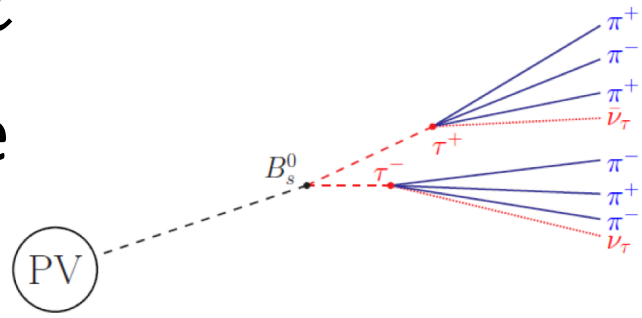
- $\mathcal{B}(B^0_{(s)} \to \tau^+\tau^-)$ enhanced by NP scenarios, previously best limit given by Babar

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 4.1 \times 10^{-3} \text{ @ 90\% C.L.}$$

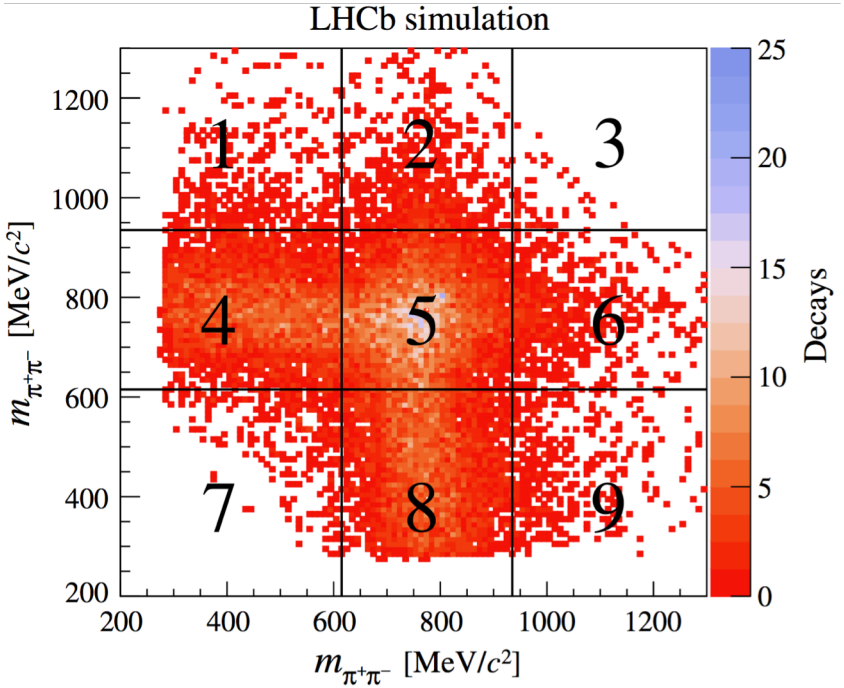
[Babar, PRL 96 (2006) 241802]

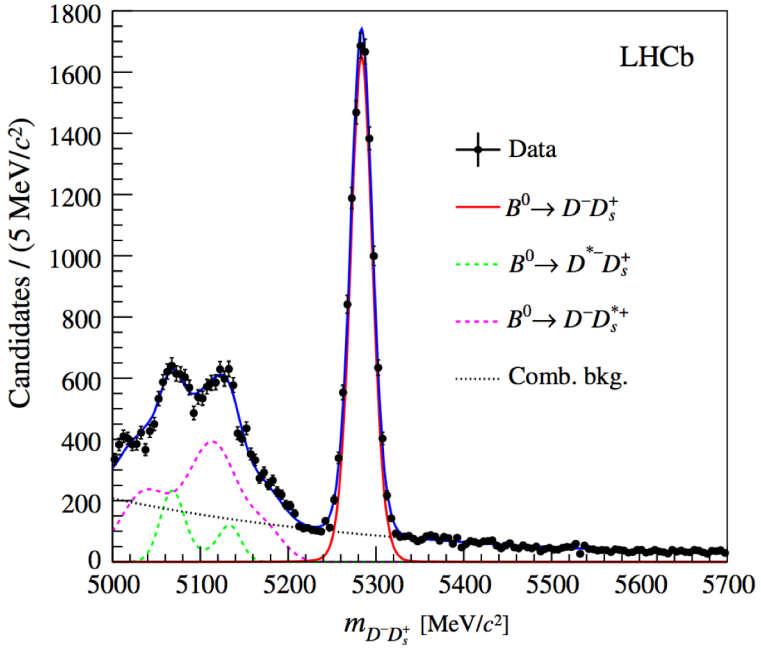
$B^0_{(s)} \to \tau^+\tau^-$

- Using $\tau^- \to 3\pi\nu_\tau(a_1)$ mode
- Normalized to $B \to D^+D_s^+$



[PRL 118 (2017) 251802]





$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 5.2(6.8) \times 10^{-3}$ @ 90 (95)% C.L.

$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.6(2.1) \times 10^{-3}$ @ 90 (95)% C.L.

$B^0_{(s)} \to \tau^+\mu^-$

- LFV, highly suppressed in SM, $\mathcal{B} \sim O(10^{-54})$, may be enhanced by NP models
  - Z', up to 10^{-8}
  - Leptoquarks, $10^{-9} - 10^{-5}$
  - Pati-Salam gauge model, $10^{-4} - 10^{-6}$
- Best limit given by Babar

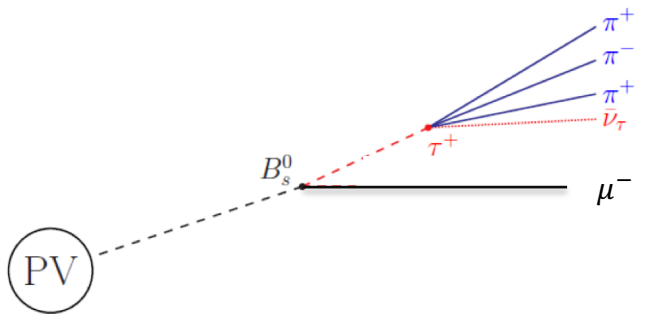
  $\mathcal{B}(B^0 \to \tau^+\mu^-) < 2.2\times10^{-5}$ at 90% CL

[Babar, PRD 77 (2008) 091104]

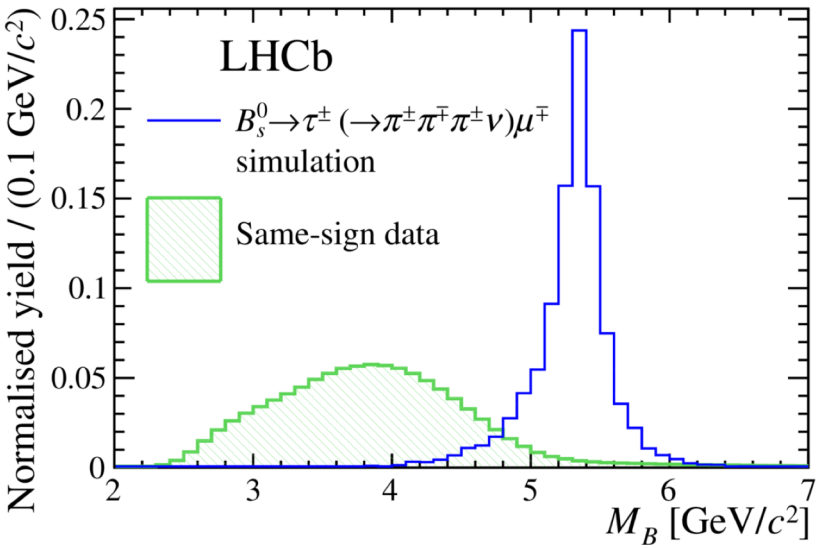
[arXiv:1705.06614]

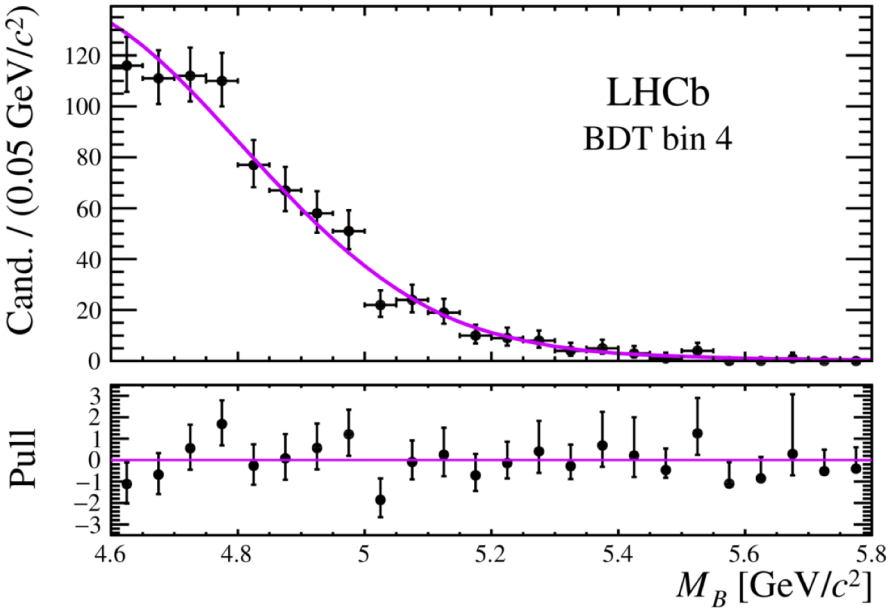
$B^0_{(s)} \to \tau^+\mu^-$

- Using $\tau^- \to 3\pi\nu_\tau(a_1)$ mode
- Normalized to $B^0 \to D^-\pi^+$



[arXiv:1705.06614]



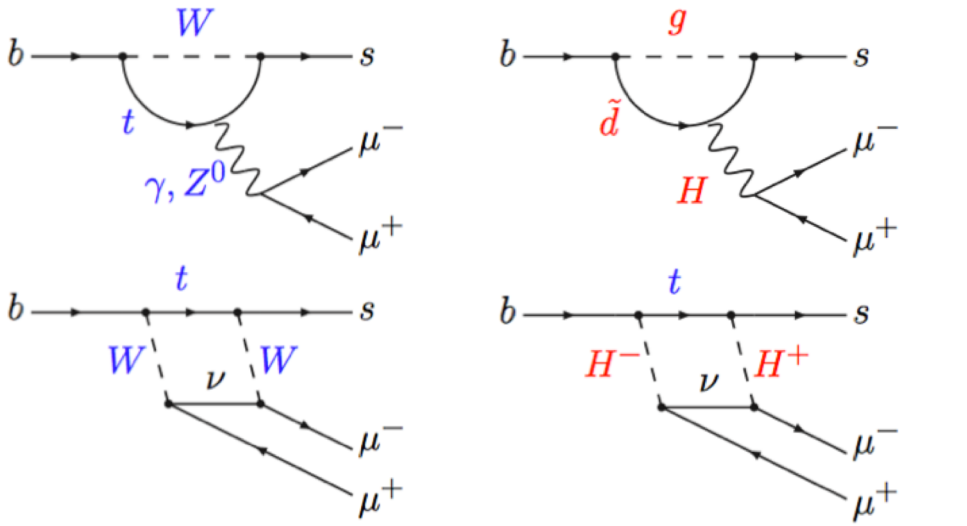


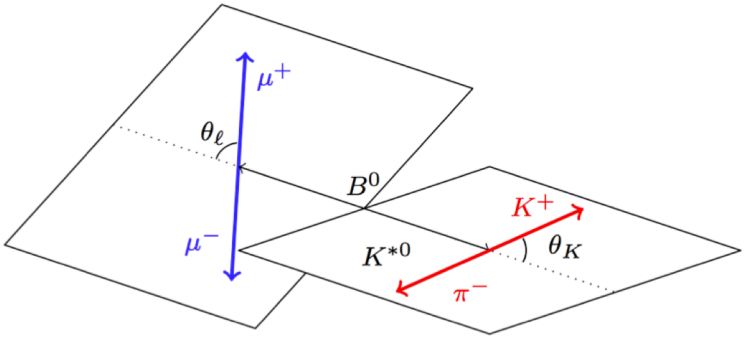
$\mathcal{B}(B^0 \to \tau^+\mu^-) < 1.4\times10^{-5}$ at 95% CL

$\mathcal{B}(B^0_s \to \tau^+\mu^-) < 4.2\times10^{-5}$ at 95% CL

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

- Rates and angular distributions sensitive to NP

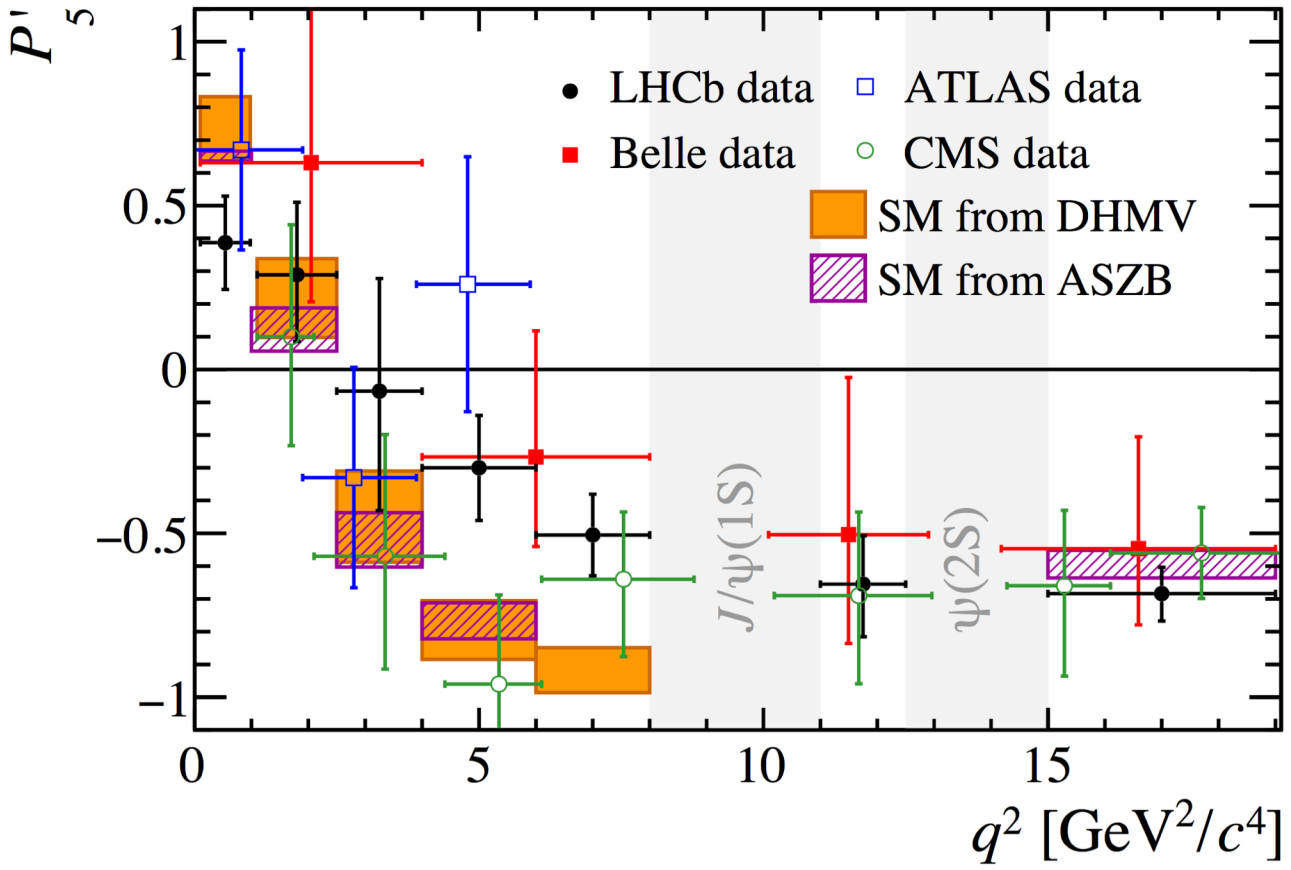




$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\big]$$

$B^0 \to K^{*0}\mu^+\mu^- : P_5'$

- LHCb updated with 3 fb^{-1}, anomaly still there
- Also measured by Belle, ATLAS, CMS

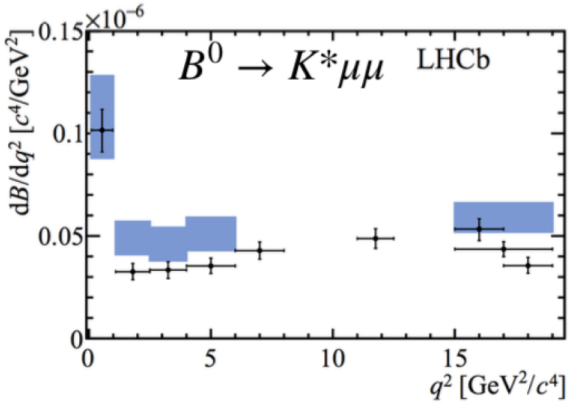


[LHCb, JHEP 02 (2016) 104]
[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

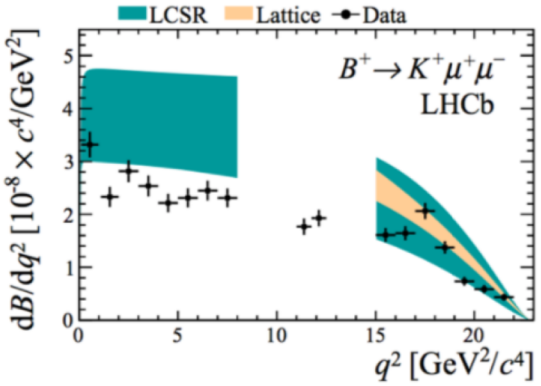
Branching fraction of $b \to s\ell^+\ell^-$

- Some tensions seen

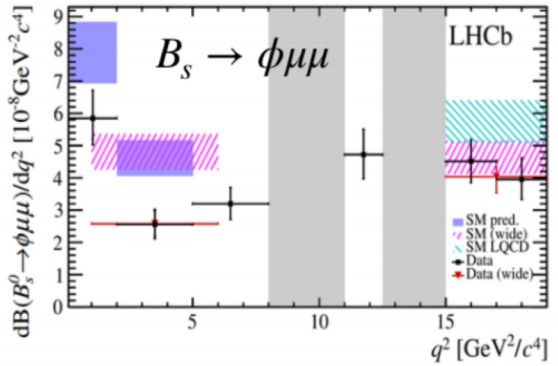
JHEP 11 (2016) 047



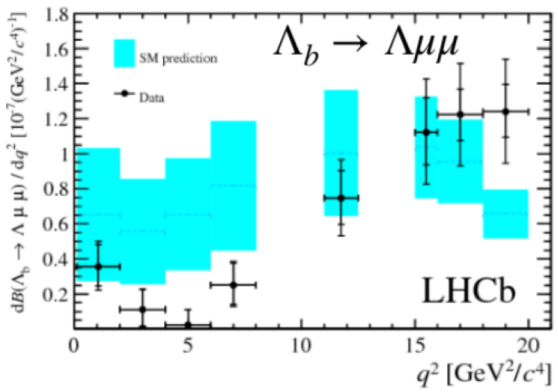
JHEP 06 (2014) 133



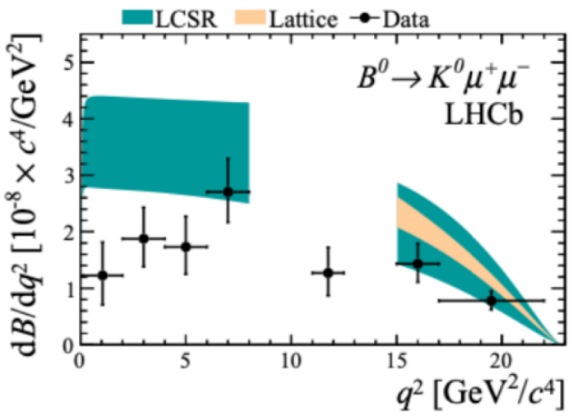
JHEP 09 (2015) 179



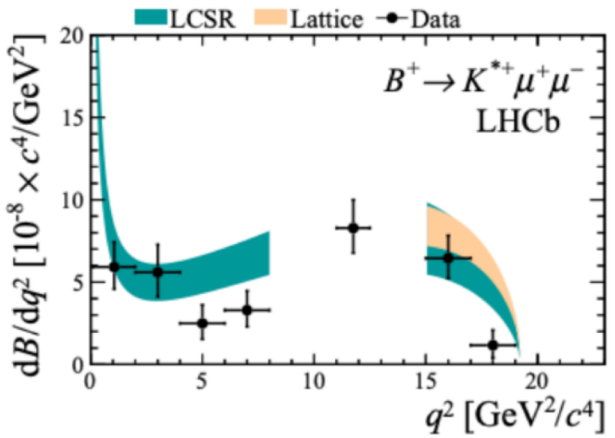
JHEP 06 (2015) 115



JHEP 06 (2014) 133

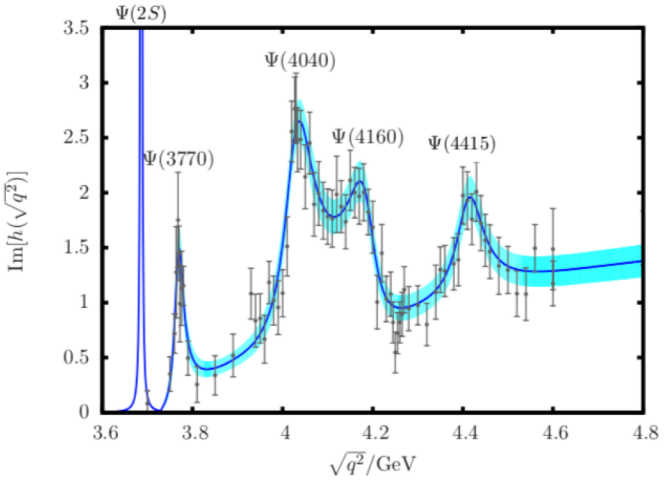


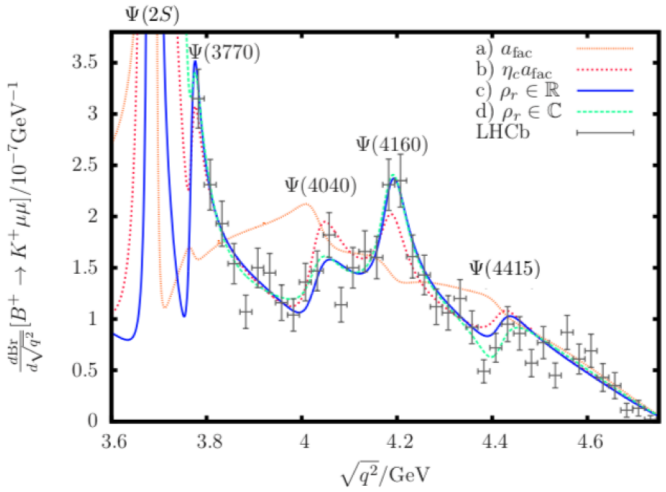
JHEP 06 (2014) 133



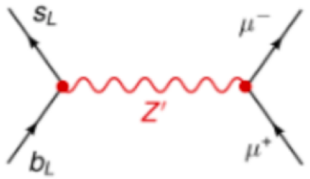
New physics, or QCD?

- Charm loop effects? [Lyon, Zwicky, arXiv:1406.0566]
  - Large non-factorisable effects (or NP) required to have consistent picture between BESII $e^+e^- \to$ hadrons data and the LHCb result

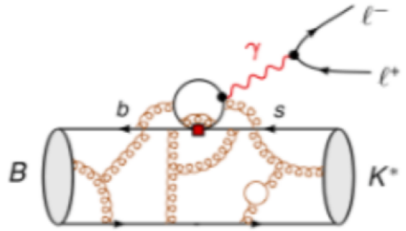




Optimist's view point



Pessimist's view point

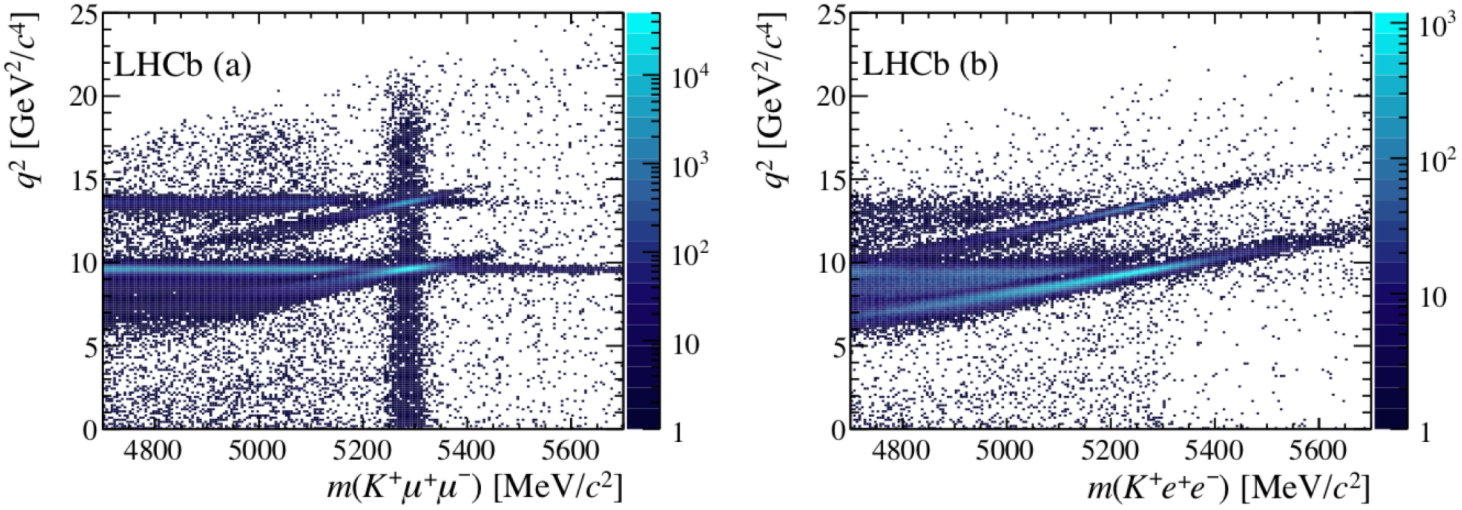


$\mathcal{R}_K$

[PRL 113 (2014) 151601]

- $\mathcal{R}_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-3})$ in the SM
- $B^+ \to J/\psi K^+$ as normalization channel, double ratio used to cancel systematic uncertainties

$$\mathcal{R}_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right)\left(\frac{\varepsilon_{K^+e^+e^-}}{\varepsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\varepsilon_{J/\psi(\mu^+\mu^-)K^+}}{\varepsilon_{J/\psi(e^+e^-)K^+}}\right)$$



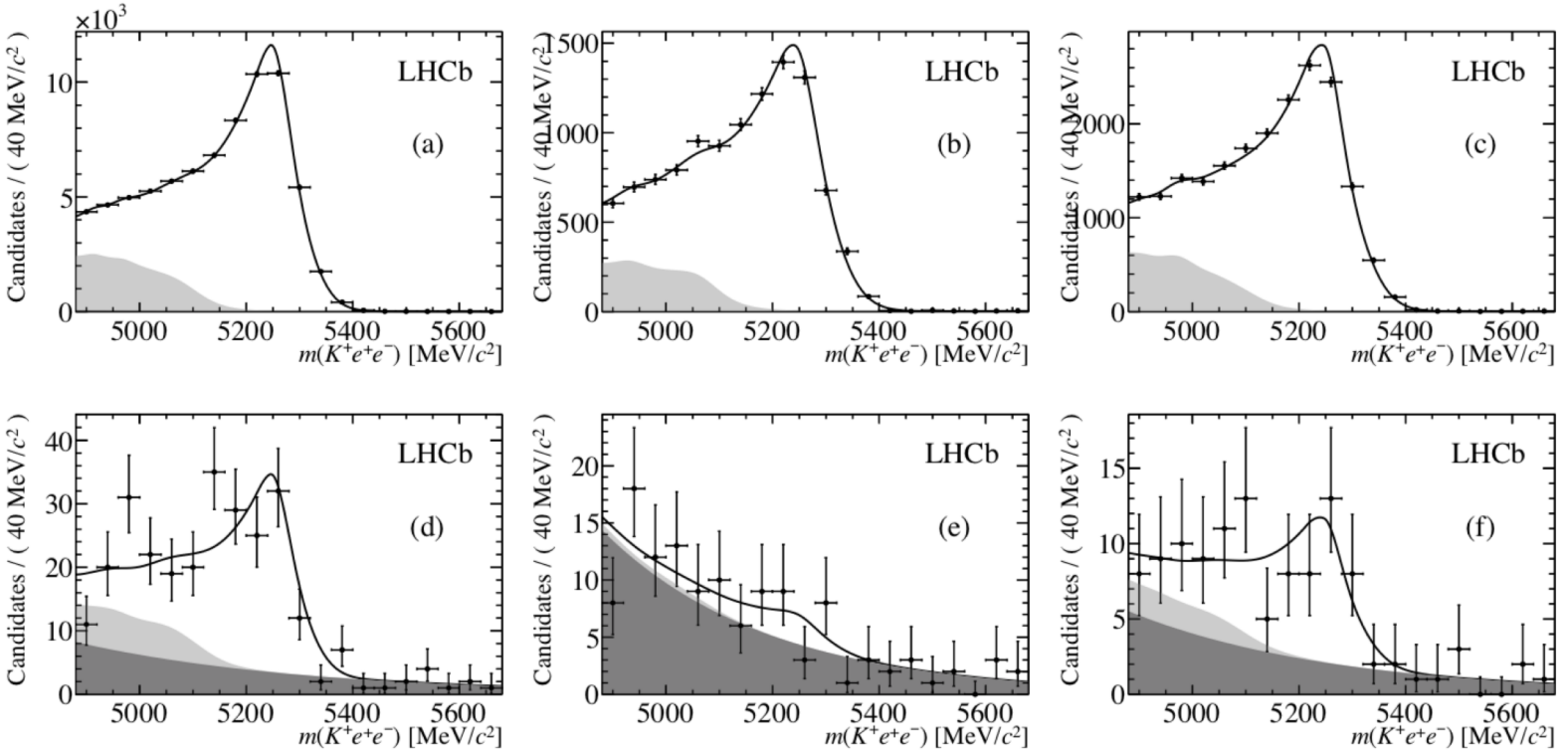
- Analysis done in the experimentally and theoretically favoured region $1 < q^2 < 6\ \mathrm{GeV}^2/c^4$

$\mathcal{R}_K$, signal yields

[PRL 113 (2014) 151601]

- $B^+ \to K^+ e^+ e^-$ split by the way how the signal is triggered

trigger category	electron	hadron	neither (TIS)
$e^+e^-K^+$	172^{+20}_{-19}	20^{+16}_{-14}	62 ± 13
$J/\psi(e^+e^-)K^+$	62324 ± 318	9337 ± 124	16796 ± 165



- Muon channel yields 5 times higher: $N(B^+ \to \mu^+\mu^- K^+) = 1226 \pm 41$

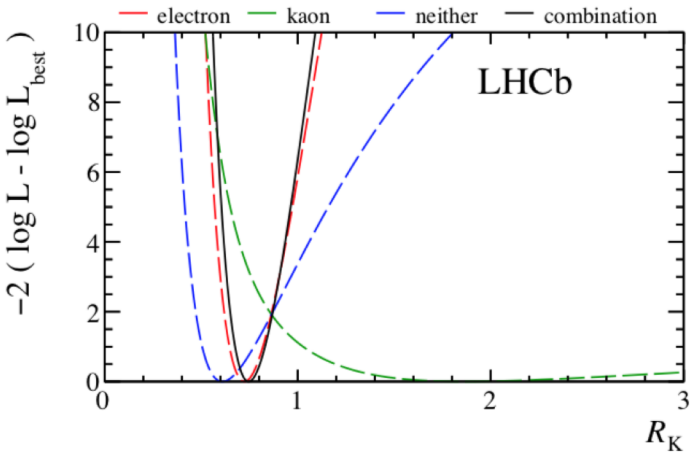
$\mathcal{R}_K$, results with Run-I data

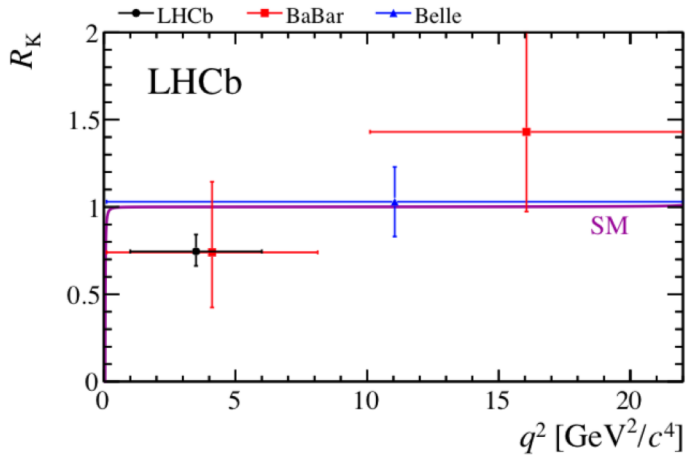
- Systematic uncertainties

[PRL 113 (2014) 151601]

	$B^+ \to J/\psi(\mu^+\mu^-)K^+$	$B^+ \to K^+\mu^+\mu^-$	$B^+ \to J/\psi(e^+e^-)K^+$	$B^+ \to K^+e^+e^-$
sig models	-	-	-1.0%	-1.0%
bkg models	-	-	+0.0%	+0.5%
bin migration	-	-	-	1.6%
trigger efficiency	-	3%	-	3%
Kaon PID	+0.2%	-0.1%	-2.0%	-1.9%
Electron PID	-	-	+3.0%	+3.0%
Muon PID	-0.1%	+0.1%	-	-
K-e veto	-	-	+0.1%	+0.3%

- $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$, compatible with SM within 2.6σ



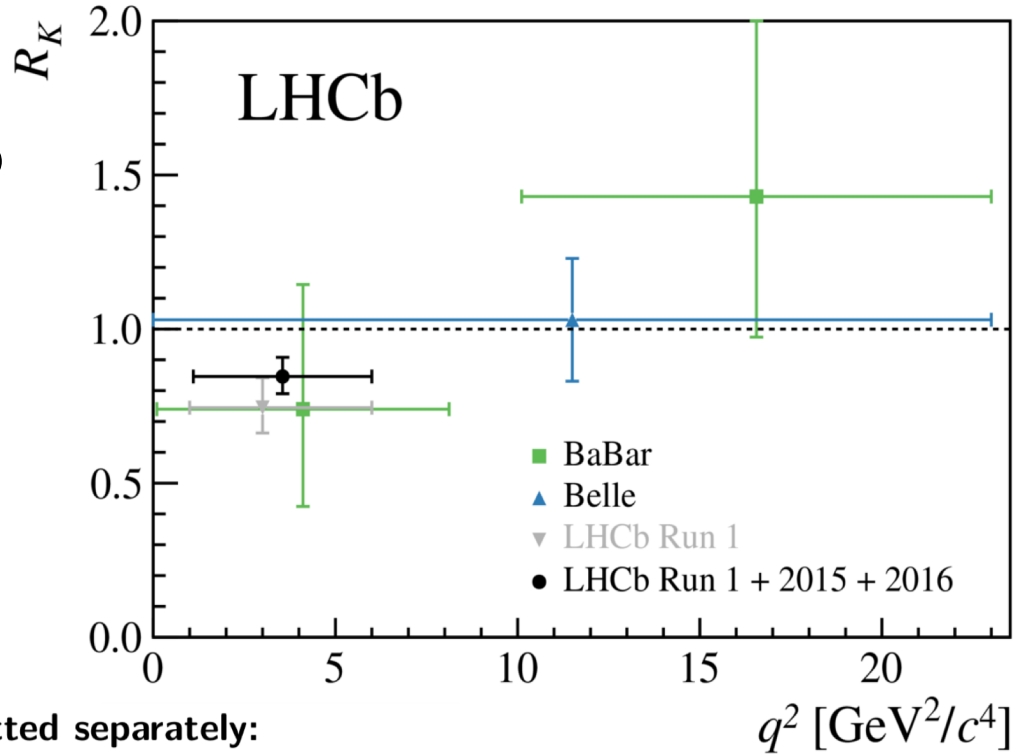


$\mathcal{R}_K$, updated results

- Include 2015+2016

  $\mathcal{R}_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$

  $\sim 2.5\sigma$ from SM



[PRL 122 (2019) 191801]

If instead the Run 1 and Run 2 were fitted separately:

$$R^{\text{new}}_{K\ \text{Run 1}} = 0.717^{+0.083+0.017}_{-0.071-0.016}, \qquad R_{K\ \text{Run 2}} = 0.928^{+0.089+0.020}_{-0.076-0.017},$$

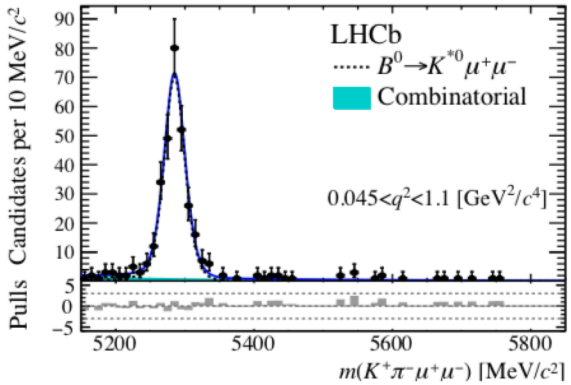
$$R^{\text{old}}_{K\ \text{Run 1}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad \text{(PRL113(2014)151601)},$$

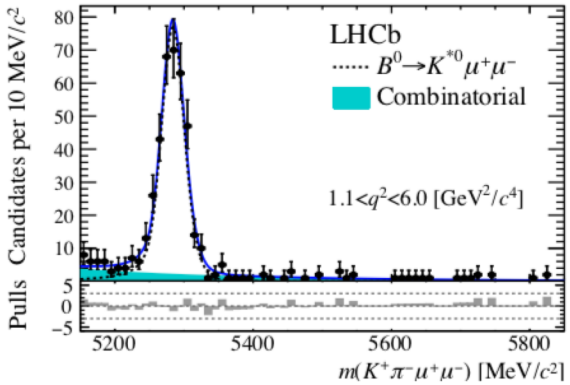
Compatibility taking correlations into account:

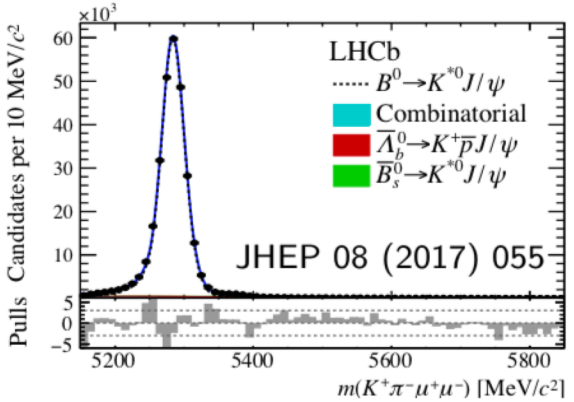
- Previous Run 1 result vs. this Run 1 result (new reconstruction selection): $< 1\ \sigma$;
- Run 1 result vs. Run 2 result: $1.9\ \sigma$.

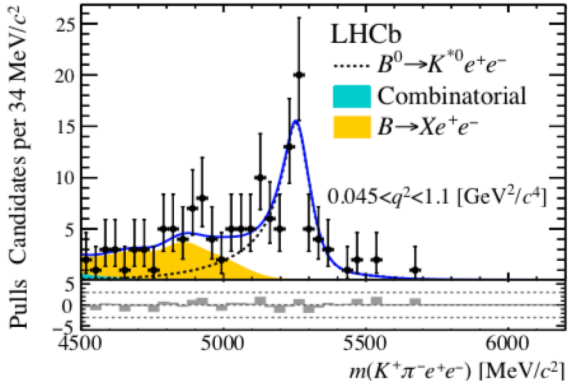
$\mathcal{R}_{K^{*0}}$

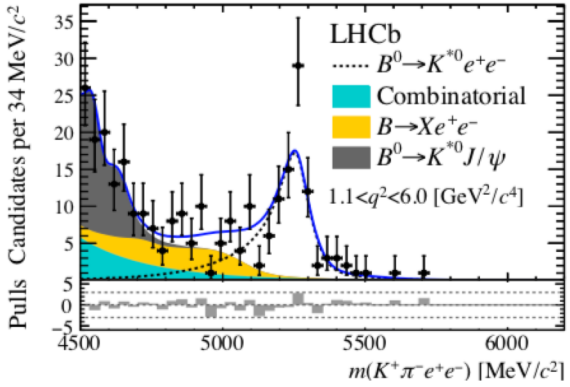
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

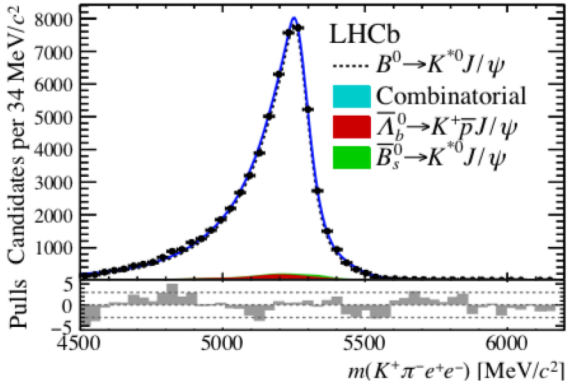






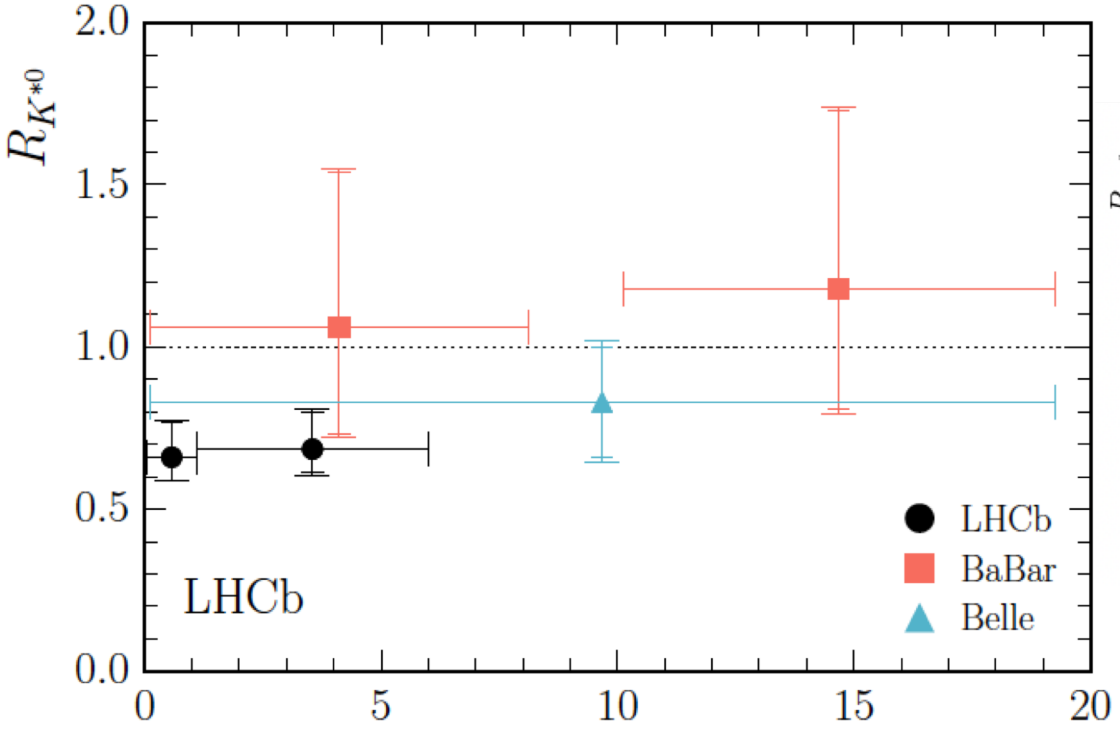


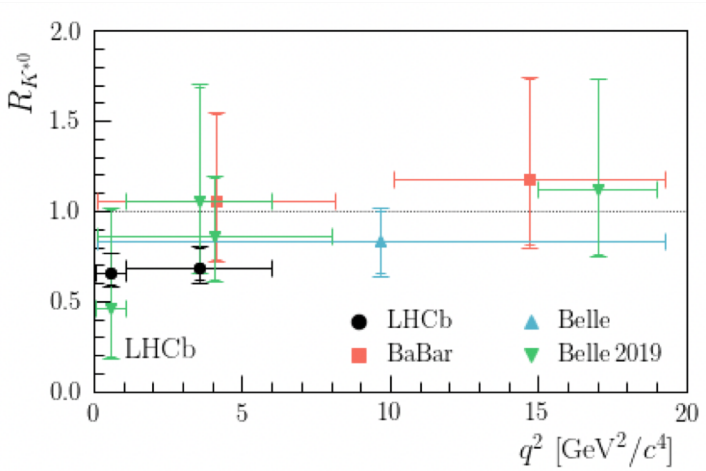




$\mathcal{R}_{K^{*0}}$, results with Run-I data

- Deviations from SM seen by LHCb ($\sim 2.4\sigma$)

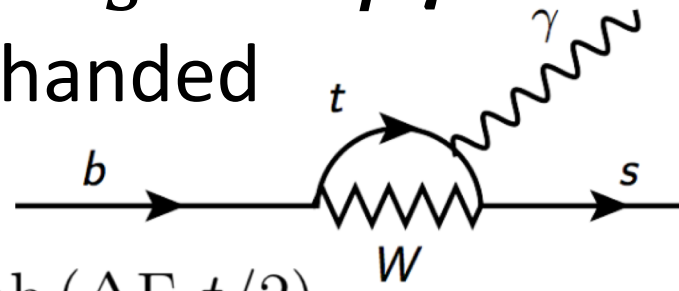




- JHEP 08 (2017) 055
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

Photon polarization in $B_s^0 \to \phi\gamma$

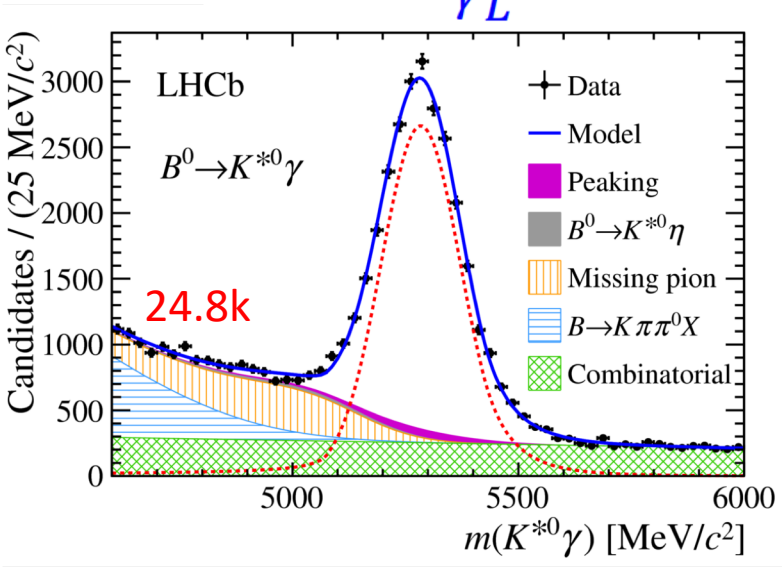
- Photons in $b \to s\gamma$ mainly left-handed
- Time-dependent signal rate

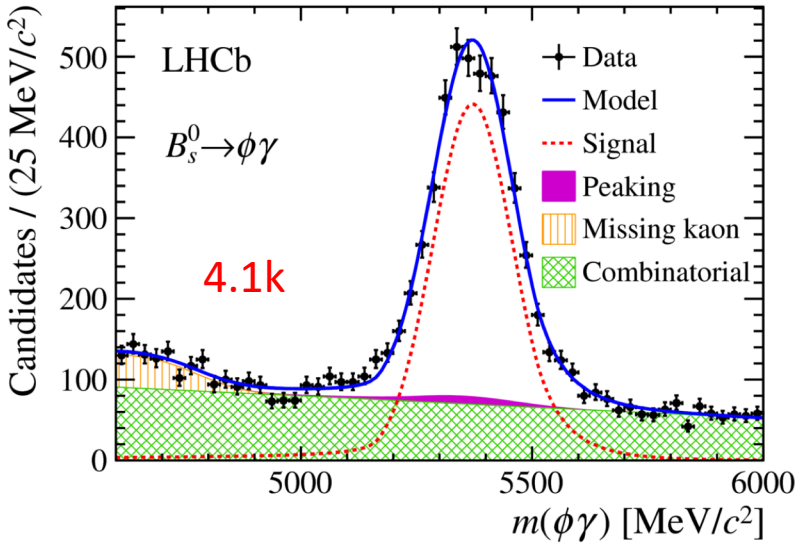


$$\mathcal{P}(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma_s t/2) + \zeta C\cos(\Delta m_s t) - \zeta S\sin(\Delta m_s t)\}$$

with $\mathcal{A}^{\Delta} \propto 2\frac{\gamma_R}{\gamma_L} \cdot \mathcal{A}^{\Delta}_{\rm SM} = 0.05 \pm 0.03$

[PRL 118 (2017) 021801]





$B_s^0 \to \phi\gamma$, untagged analysis

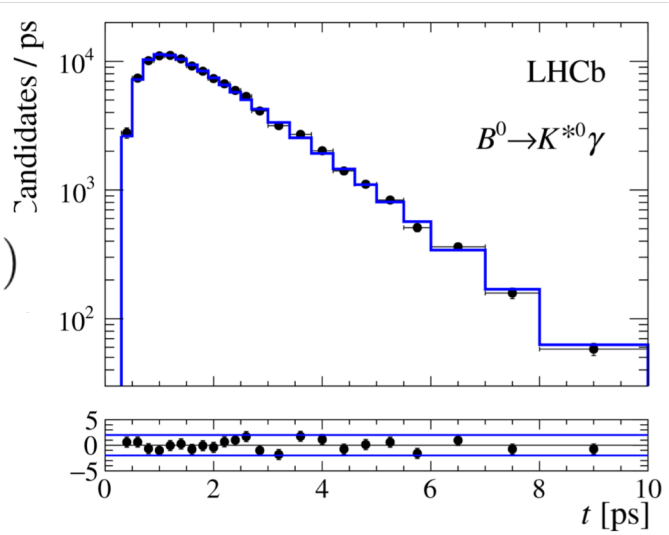
- Assuming equal mixture of $B_s^0/\bar{B}_s^0$, simplified

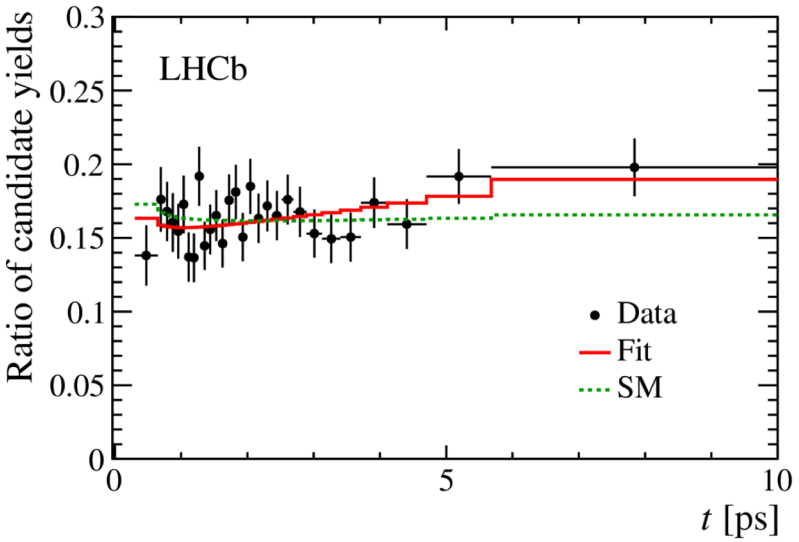
$$\mathcal{P}(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma_s t/2)$$

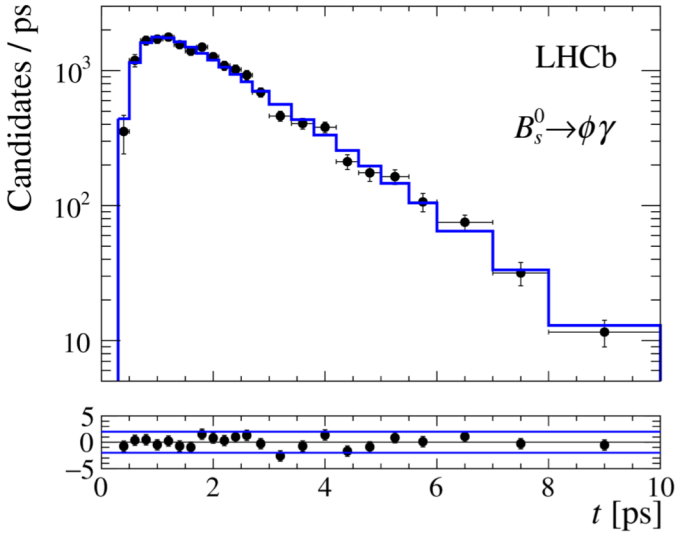
- Measured

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

[PRL 118 (2017) 021801]







$B_s^0 \to \phi\gamma$, tagged analysis

- Same dataset, with flavor-tagging

$$\mathcal{P}(t) \propto e^{-\Gamma_s t}\Big\{ \cosh\left(\Delta\Gamma_s t/2\right) - \mathcal{A}^{\Delta} \sinh\left(\Delta\Gamma_s t/2\right) + \zeta\, C \cos\left(\Delta m_s t\right) - \zeta\, S \sin\left(\Delta m_s t\right)\Big\}$$

$$\mathcal{A}^{\Delta}_{\phi\gamma} \approx \frac{\mathrm{Re}\left(e^{-i\phi_s} C_7 C_7'\right)}{|C_7|^2 + |C_7'|^2} \qquad S^{\Delta}_{\phi\gamma} \approx \frac{\mathrm{Im}\left(e^{-i\phi_s} C_7 C_7'\right)}{|C_7|^2 + |C_7'|^2}$$

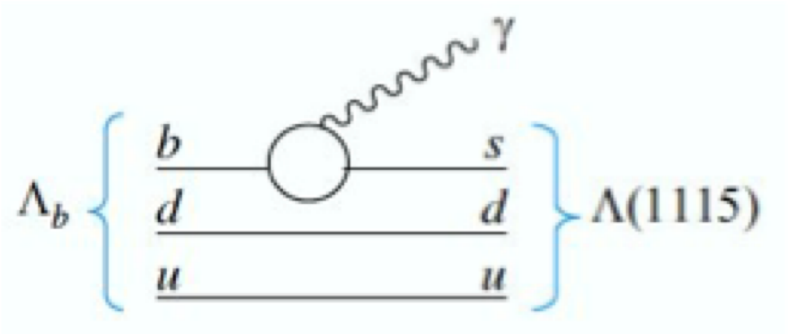
- First measurement of S/C in radiative B_s^0 decay

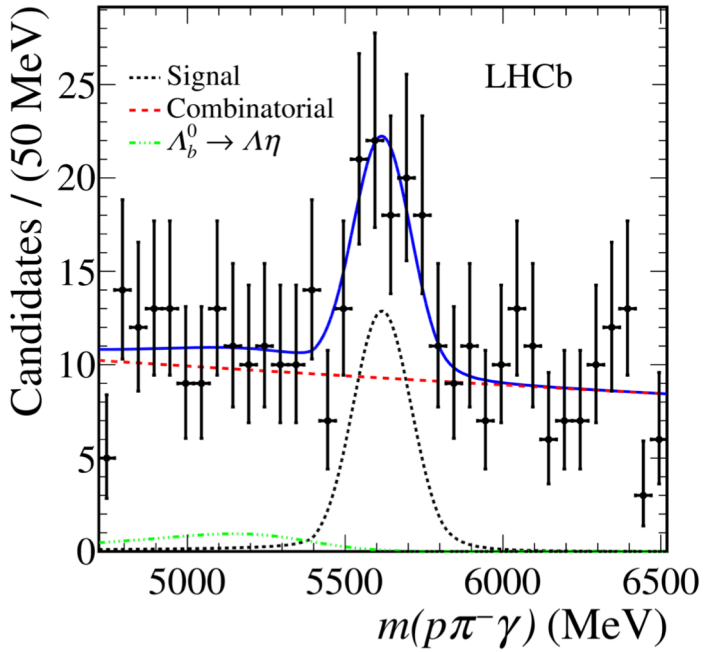
$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11,$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11,$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17,$$

[arXiv:1905.06284]

Observation of $\Lambda_b^0 \to \Lambda\gamma$

- Baryonnic $b \to s\gamma$ not observed yet. Upper limits set by CDF $\mathcal{B} < 1.9\times10^{-3}$ [CDF, PRD 66 (2002) 112002]
- In SM, $\mathcal{B}\sim0.06 - 1\times10^{-5}$





- First observation, BR:

$$\mathcal{B}\left(\Lambda_b^0 \to \Lambda\gamma\right) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7)\times10^{-6}$$

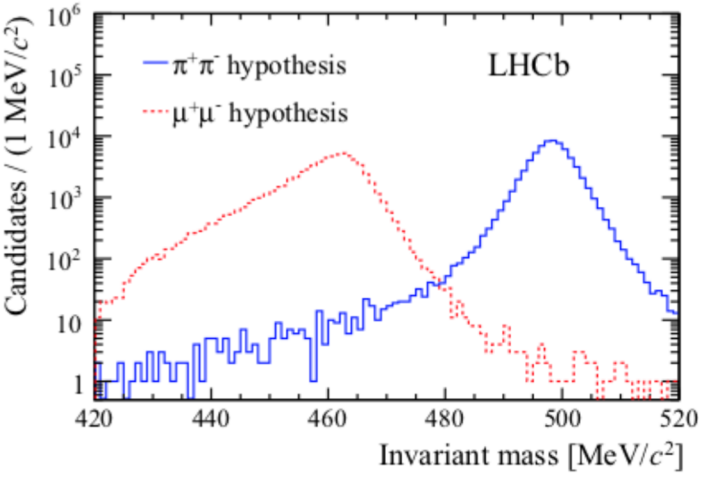
[PRL 123 (2019) 031801]

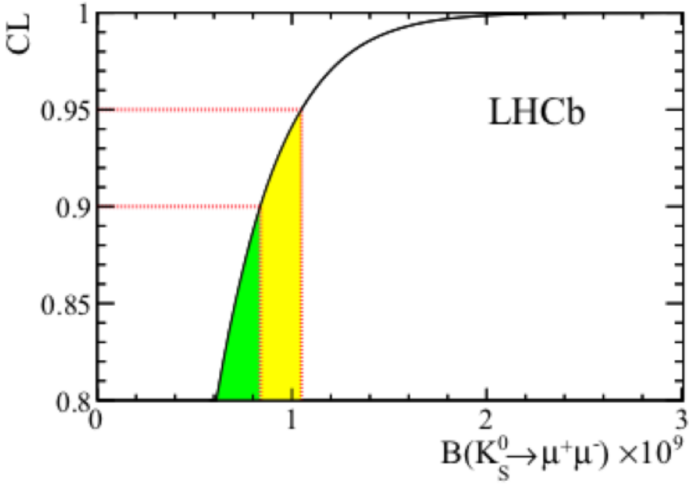
$K_S^0 \to \mu^+\mu^-$

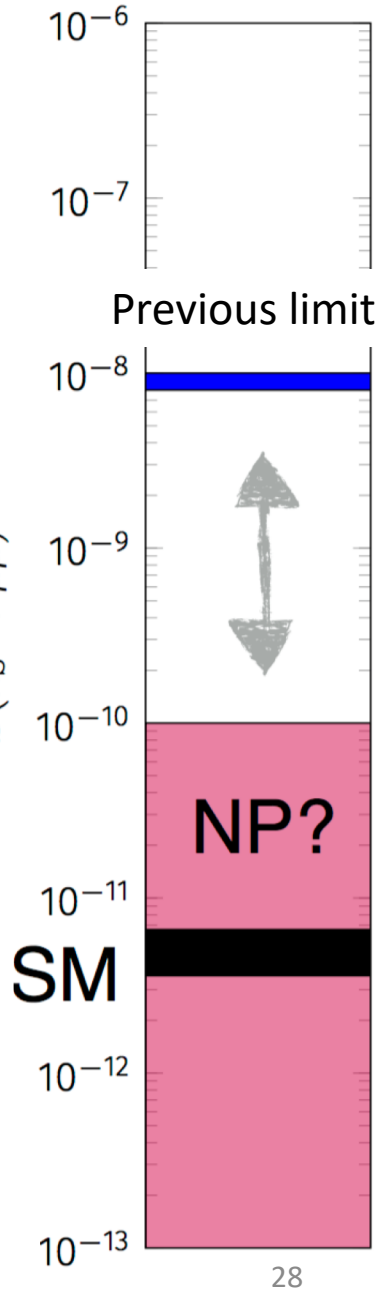
- SM prediction: BR=(5.0±1.5)×10^{-12}, can be enhanced by up to factor 100
- $K_S^0 \to \pi^+\pi^-$: control channel, main Bkg

$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 0.8(1.0) \times 10^{-9}$ @ 90 (95)% C.L.

[EPJC 77 (2017) 678]







Summary

- LHCb performed the world-leading measurements of rare *B* decays:
  - Very rare decays, e.g., $B^0_{(s)} \to \mu^+\mu^-$, $B^0_{(s)} \to \tau^+\tau^-$
  - LFV, e.g., $B^0_{(s)} \to \tau^+\mu^-$
  - Electroweak penguin, e.g., $B^0 \to K^{*0}\mu^+\mu^-$, $\mathcal{R}_{K^{(*0)}}$
  - Radiative, e.g., $B^0_s \to \phi\gamma$, $\Lambda^0_b \to \Lambda\gamma$
  - Rare Strange, e.g., $K^0_S \to \mu^+\mu^-$
- Your suggestions are always appreciated!