University of Chinese Academy of Sciences

Rare decays & lepton flavor universality test

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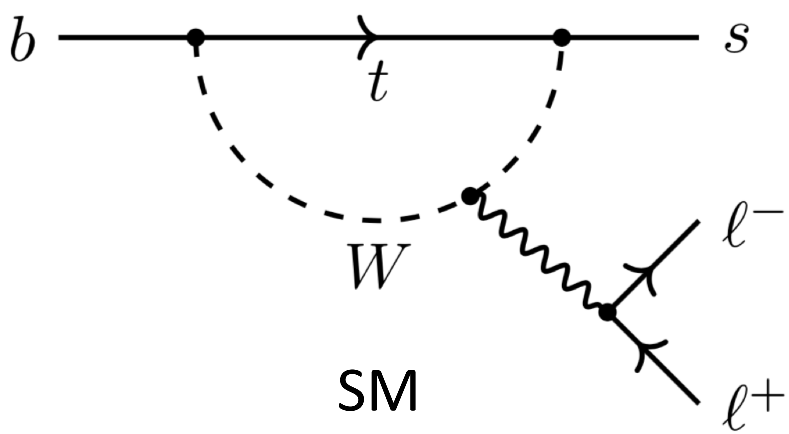
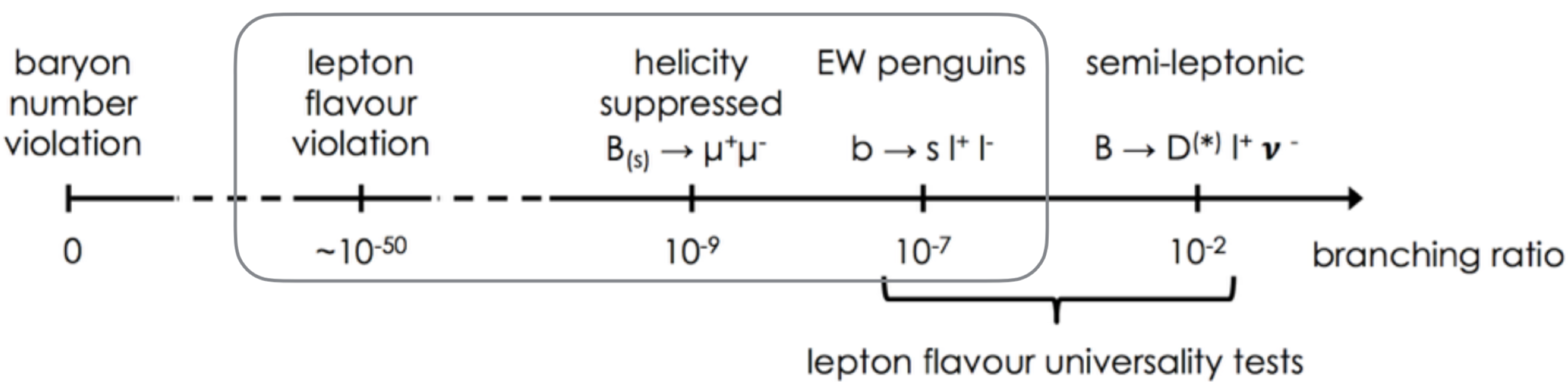
CLHCP2019 @ 大连理工大学（DLUT）

Introduction

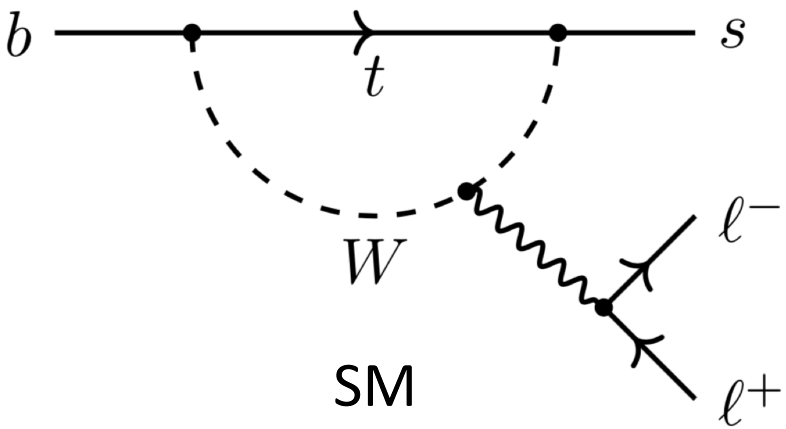
- Rare decays: suppressed in SM.

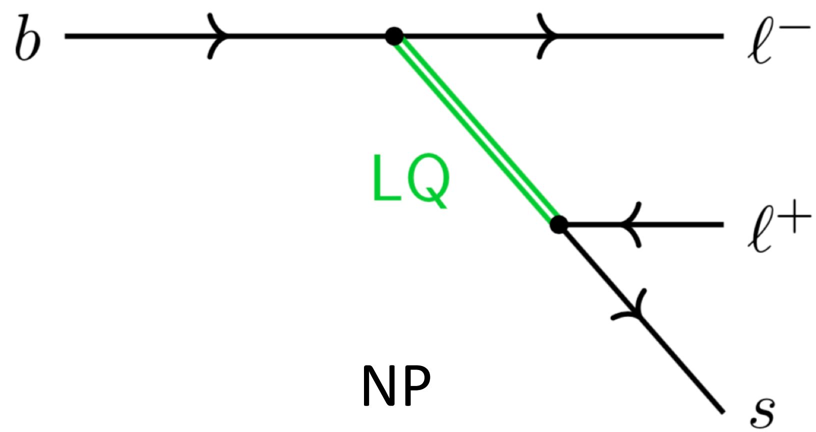


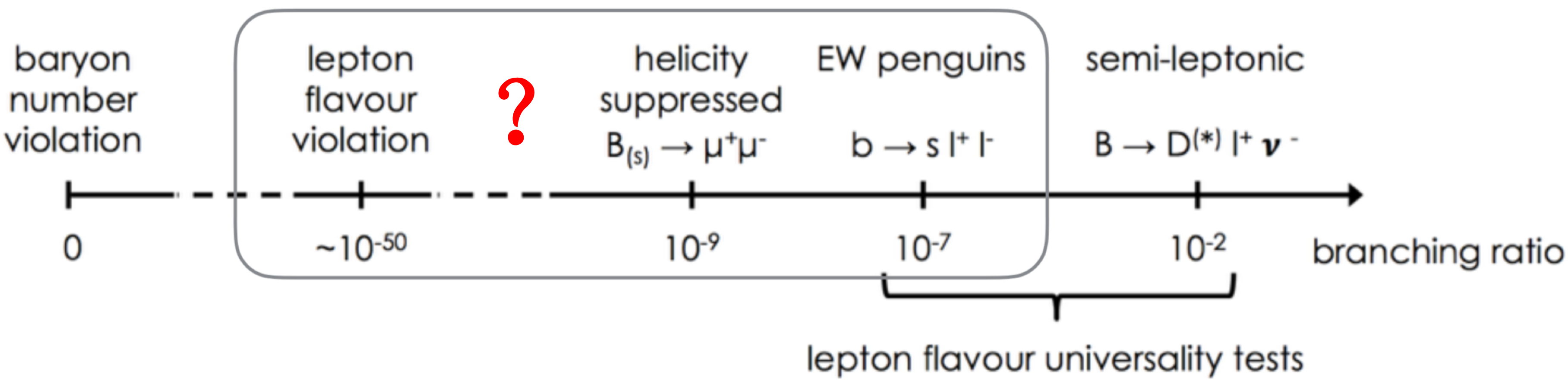


Introduction

- Rare decays: suppressed in SM. New Physics?

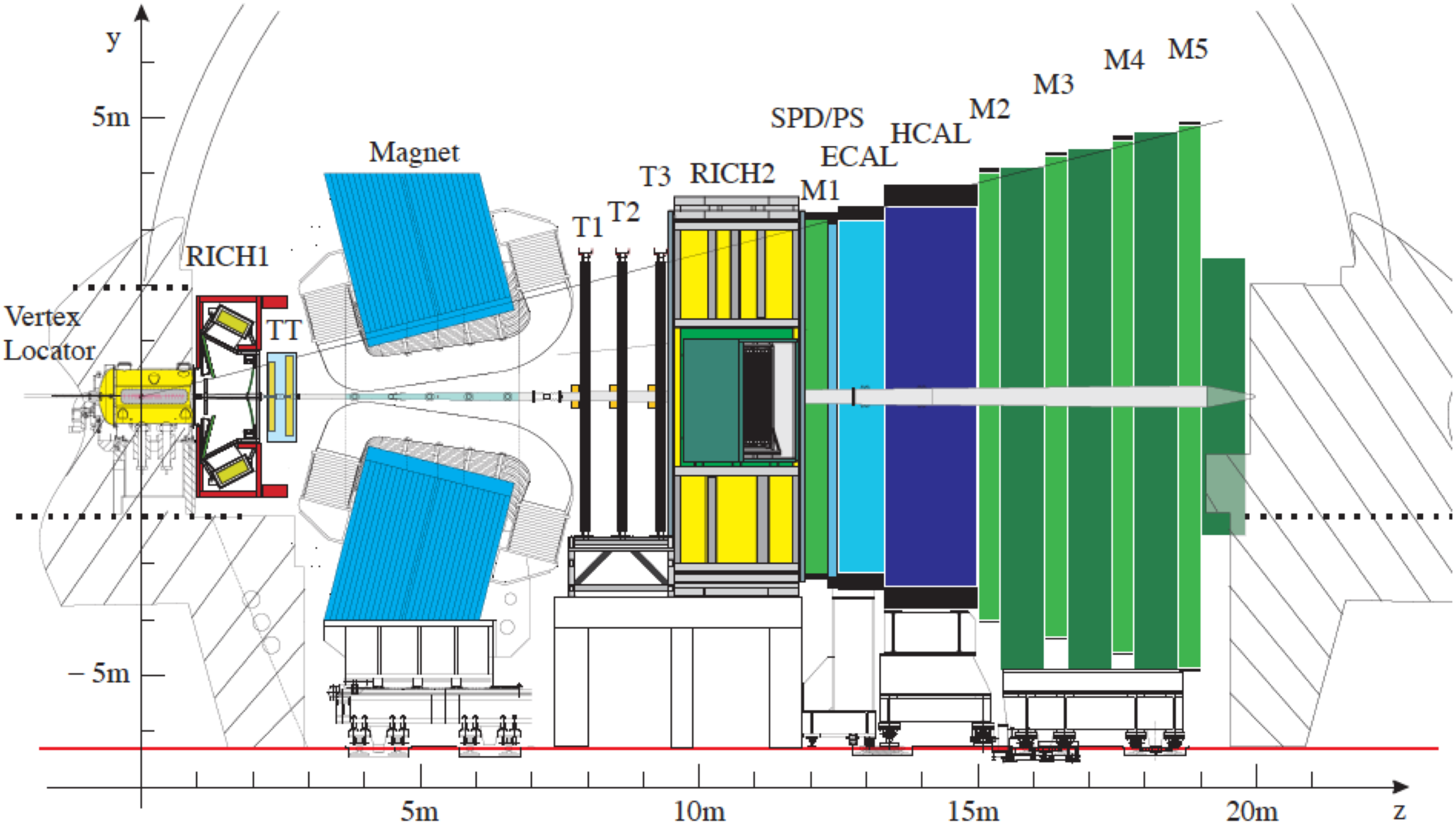




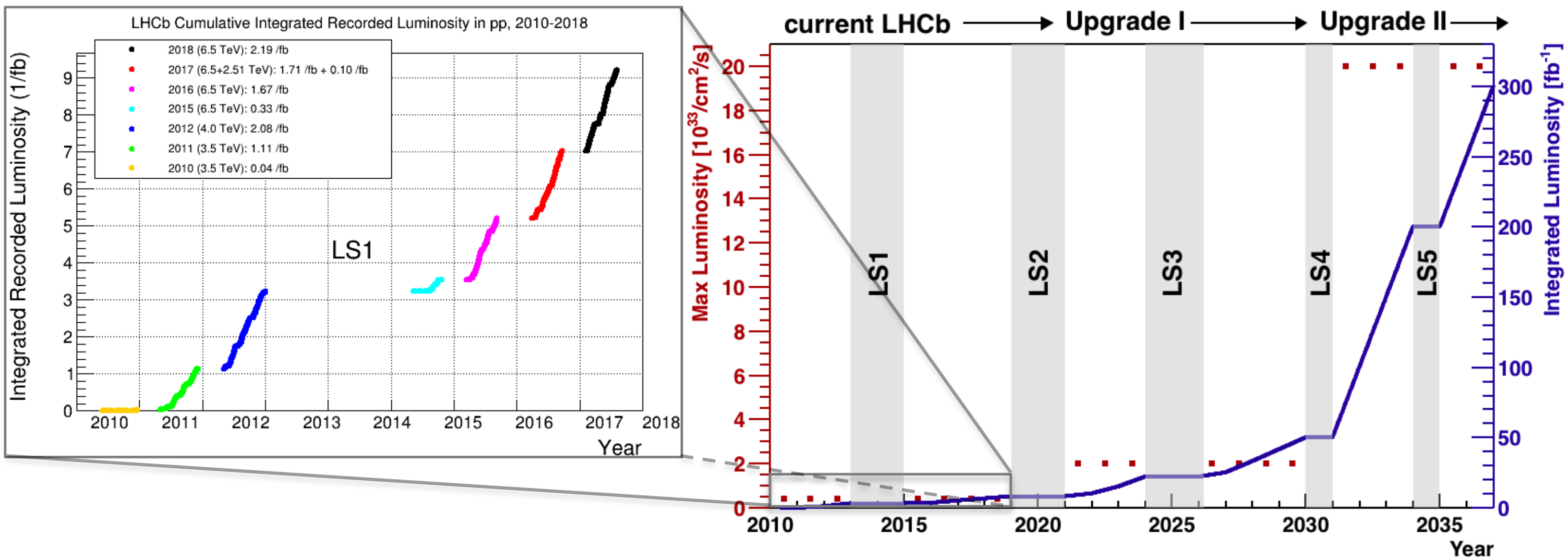


The LHCb experiment

- 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} ??

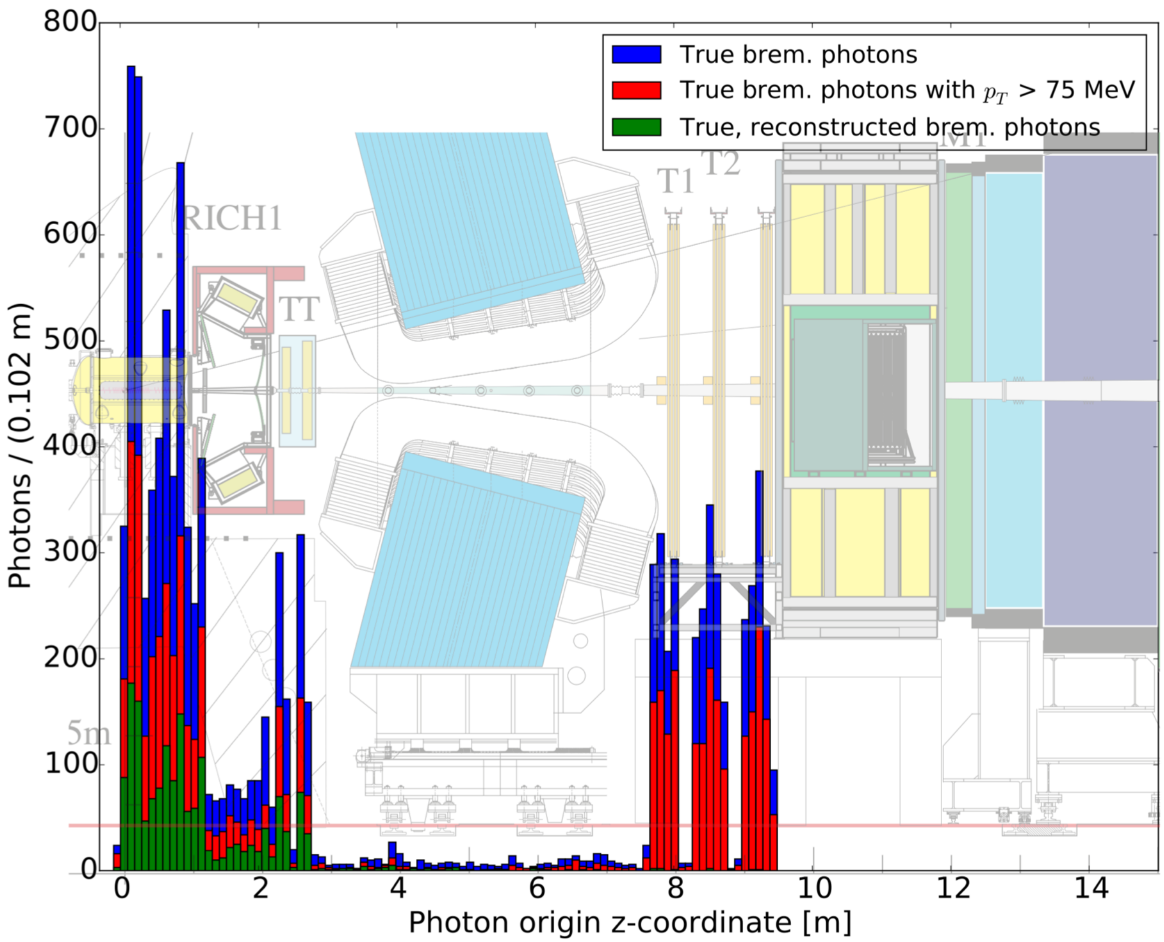
Phase-1 Upgrade!!

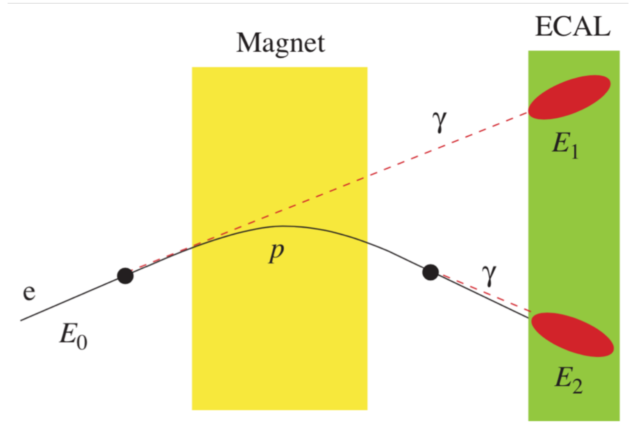
Phase-1b Upgrade!?

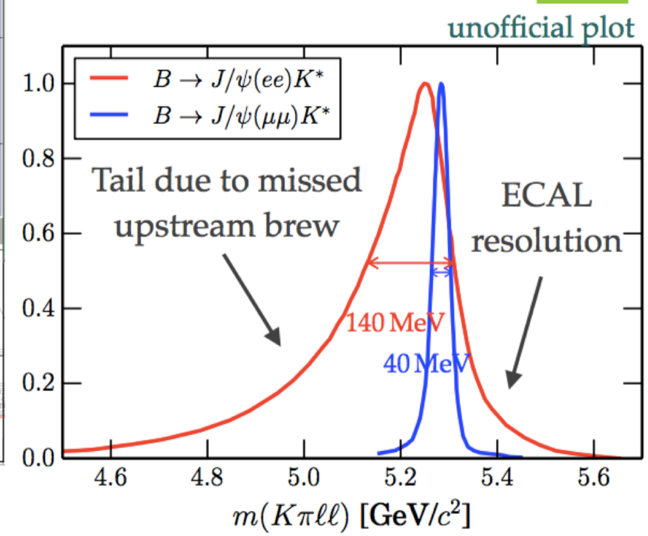
Phase-2 Upgrade??

* See Prof. J.C. Wang's talk on Sunday for the LHCb upgrades

Bremsstrahlung corrections





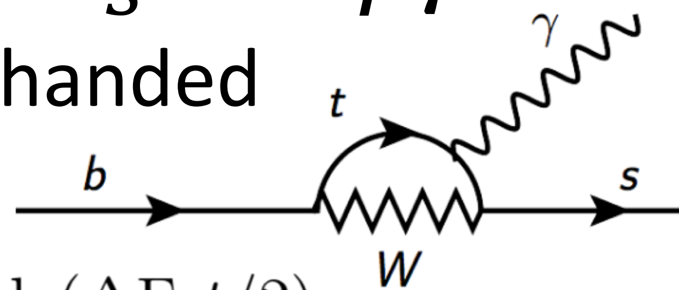


Rare decays at LHCb

- Radiative
  - $B_s^0 \to \phi\gamma, \Lambda_b^0 \to \Lambda\gamma, B^+ \to K^+\pi^+\pi^-\gamma$
- Rare charm
  - $D^0 \to \mu^+\mu^-, \Lambda_c^+ \to p\mu^+\mu^-$
- Rare strange
  - $K_S^0 \to \mu^+\mu^-, \Sigma^+ \to p\mu^+\mu^-$
- Very rare decays
  - $B_{(s)}^0 \to \mu^+\mu^-, B_{(s)}^0 \to \tau^+\tau^-, B_{(s)}^0 \to \mu^+\mu^-\mu^+\mu^-$
- Lepton flavor violation
  - $B_{(s)}^0 \to \tau^+\mu^-$, $B_{(s)}^0 \to e^+\mu^-, \tau^+ \to \mu^+\mu^-\mu^+$
- Electroweak penguin
  - $B^0 \to K^{*0}\mu^+\mu^-$, LFU

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

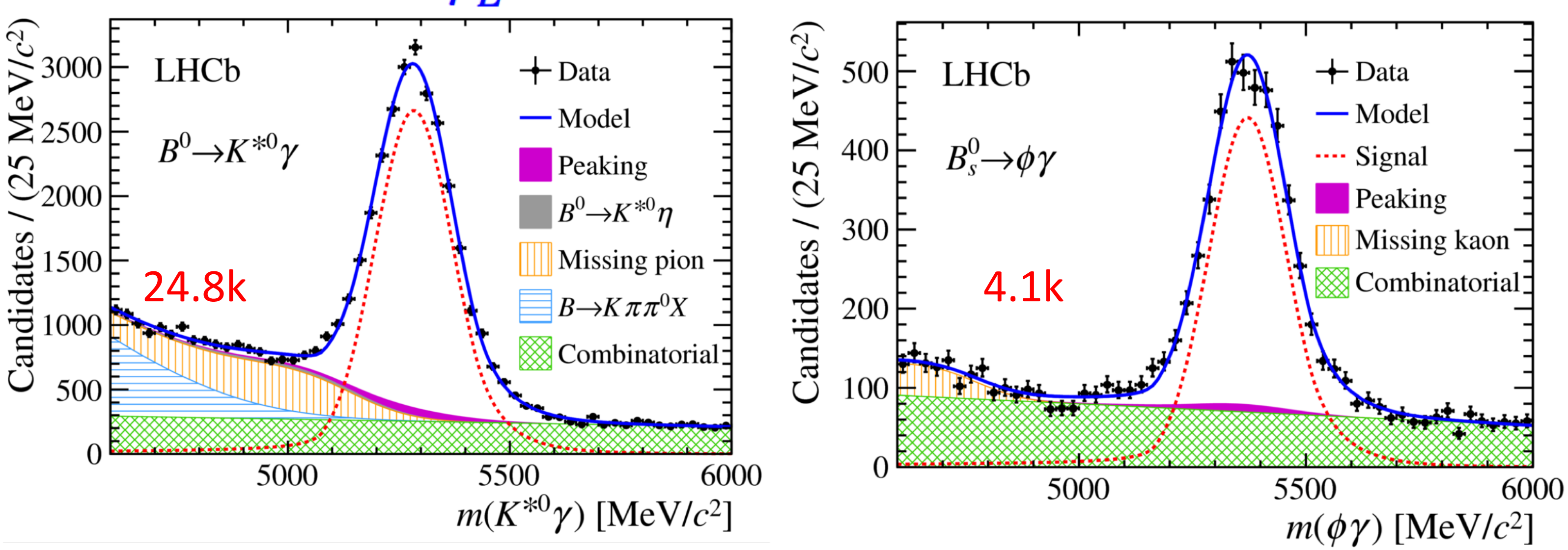
- Photons in $b \to s\gamma$ mainly left-handed
- Time-dependent signal rate



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

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

[PRL 118 (2017) 021801]



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

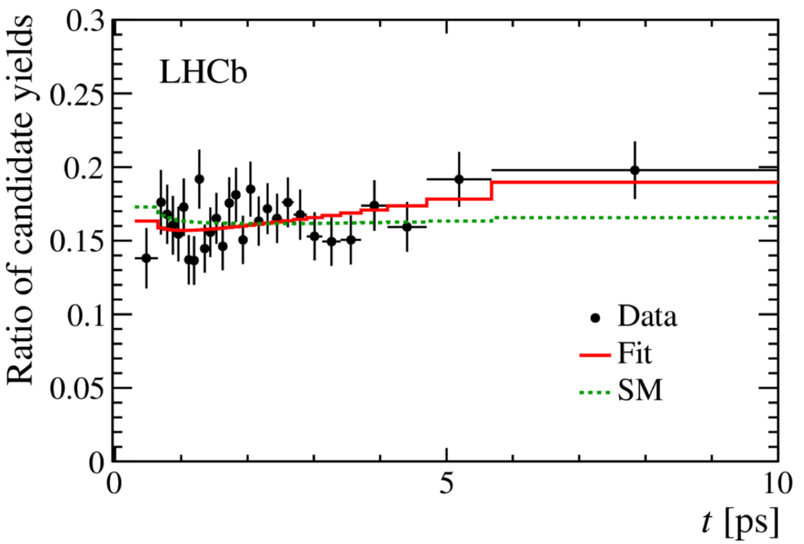
[PRL 118 (2017) 021801]

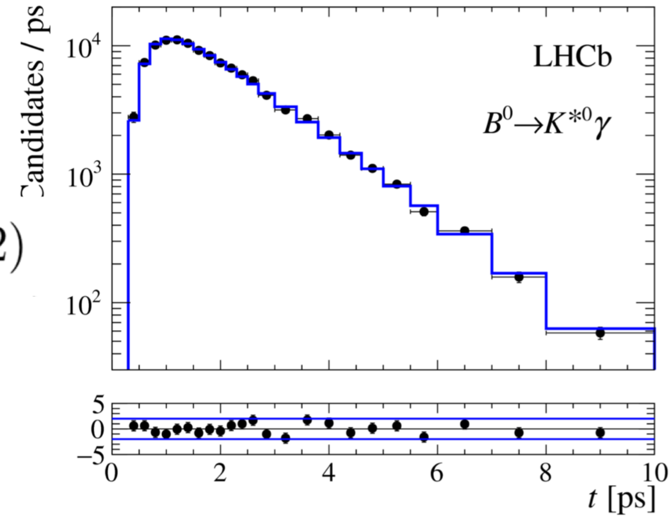
- Assuming equal mixture of $B_s^0/\bar{B}_s^0$, simplified

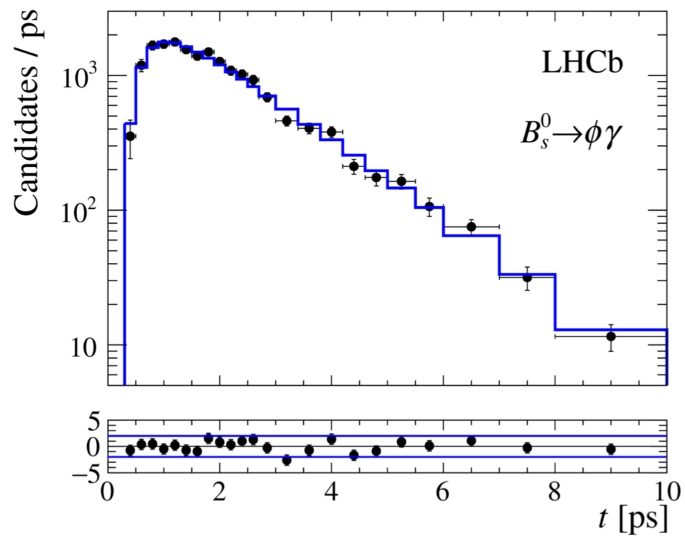
$$\mathcal{P}(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma_s t/2)$$

- Measured

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







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

[PRL 123 (2019) 081802]

- Same dataset, with flavor-tagging

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

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

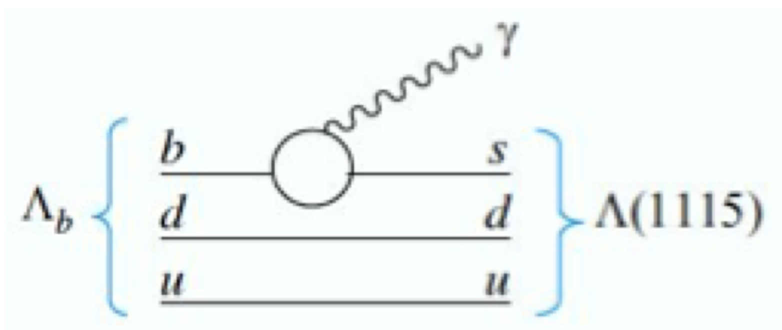
- First measurement of S/C in radiative B_s^0 decay

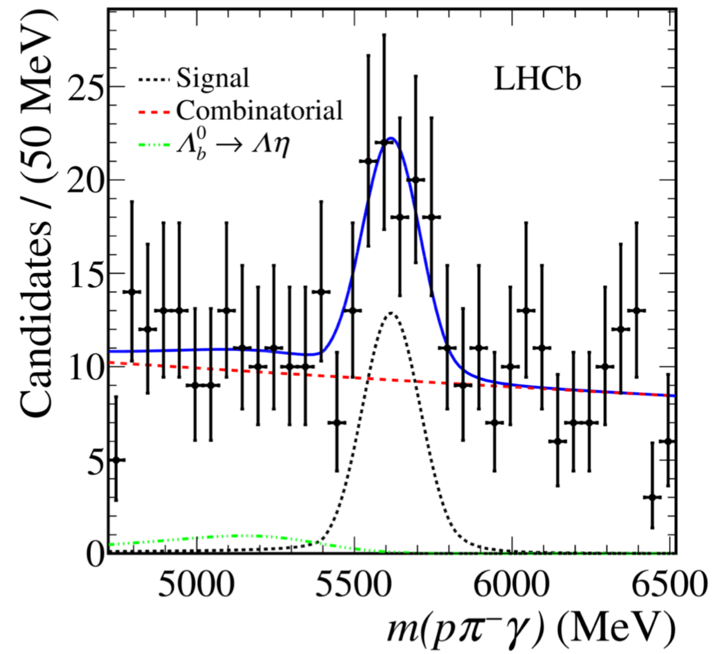
$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$

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

- Baryonnic $b \to s\gamma$ not observed yet. Upper limit set by CDF, $\mathcal{B} < 1.9{\times}10^{-3}$ [CDF, PRD 66 (2002) 112002]
- In SM, $\mathcal{B} \sim 0.06 - 1{\times}10^{-5}$

[PRL 123 (2019) 031801]





- First observation, BR:

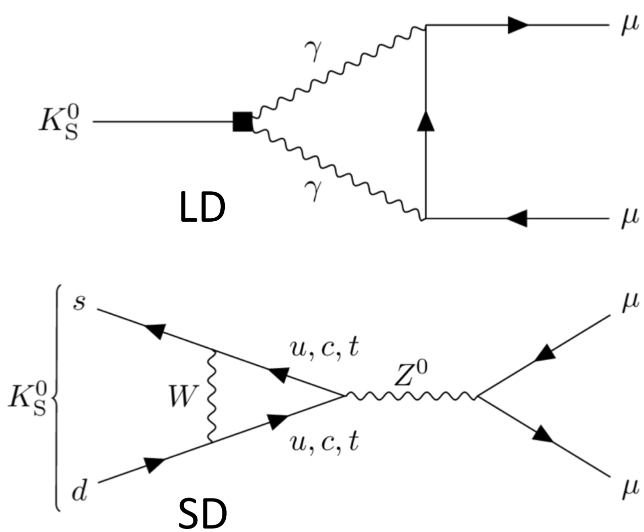
$$\mathcal{B}\left(\Lambda_b^0 \to \Lambda\gamma\right) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7){\times}10^{-6}$$

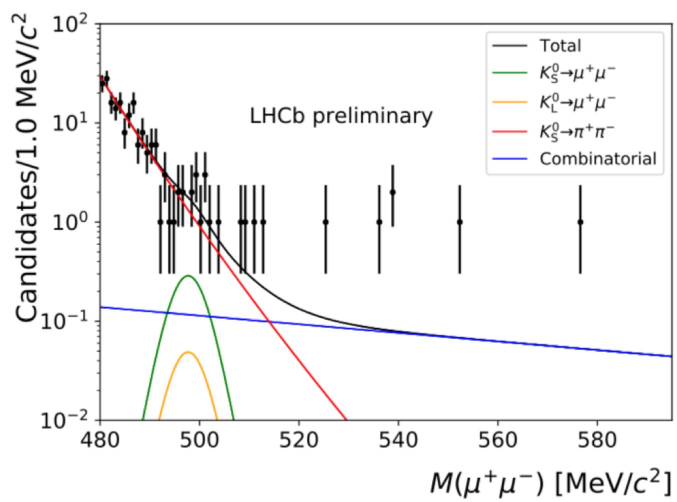
$K_S^0 \to \mu^+\mu^-$

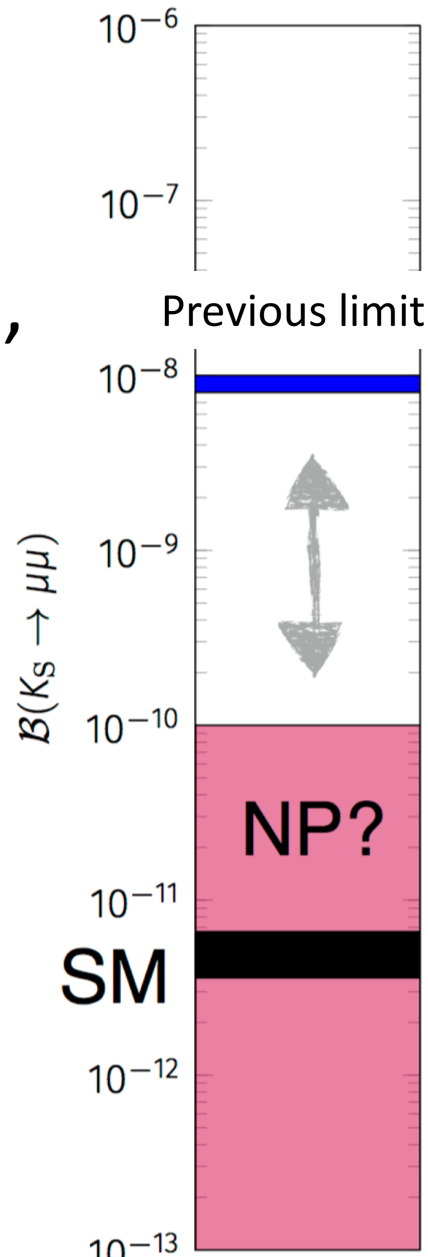
- SM predicts: $\mathcal{B} = (5.2 \pm 1.5_{\mathrm{LD}})\times 10^{-12}$, can be enhanced by up to factor 100
- $K_S^0 \to \pi^+\pi^-$: control channel, main Bkg

$$\mathcal{B}(K_{\mathrm{S}}^0 \to \mu^+\mu^-) < 2.1\,(2.4) \times 10^{-10} \text{ at } 90\ (95)\% \text{ CL}$$

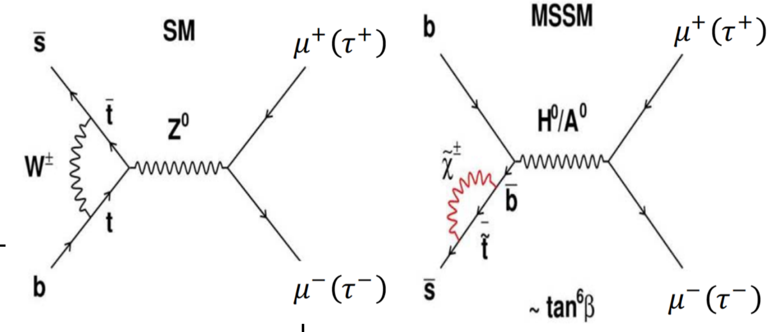
[LHCb-CONF-2019-002]



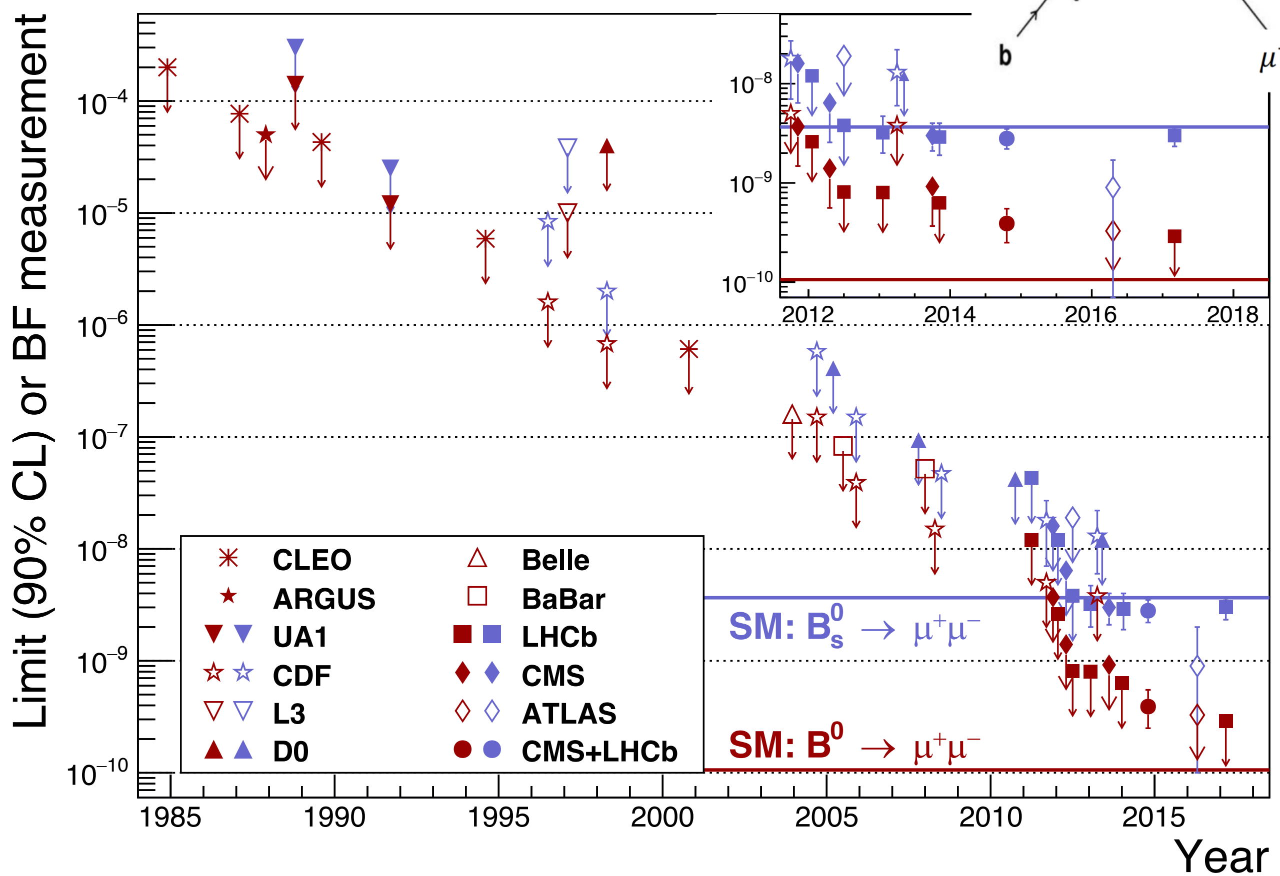




$B^0_{(s)} \to \mu^+\mu^-$



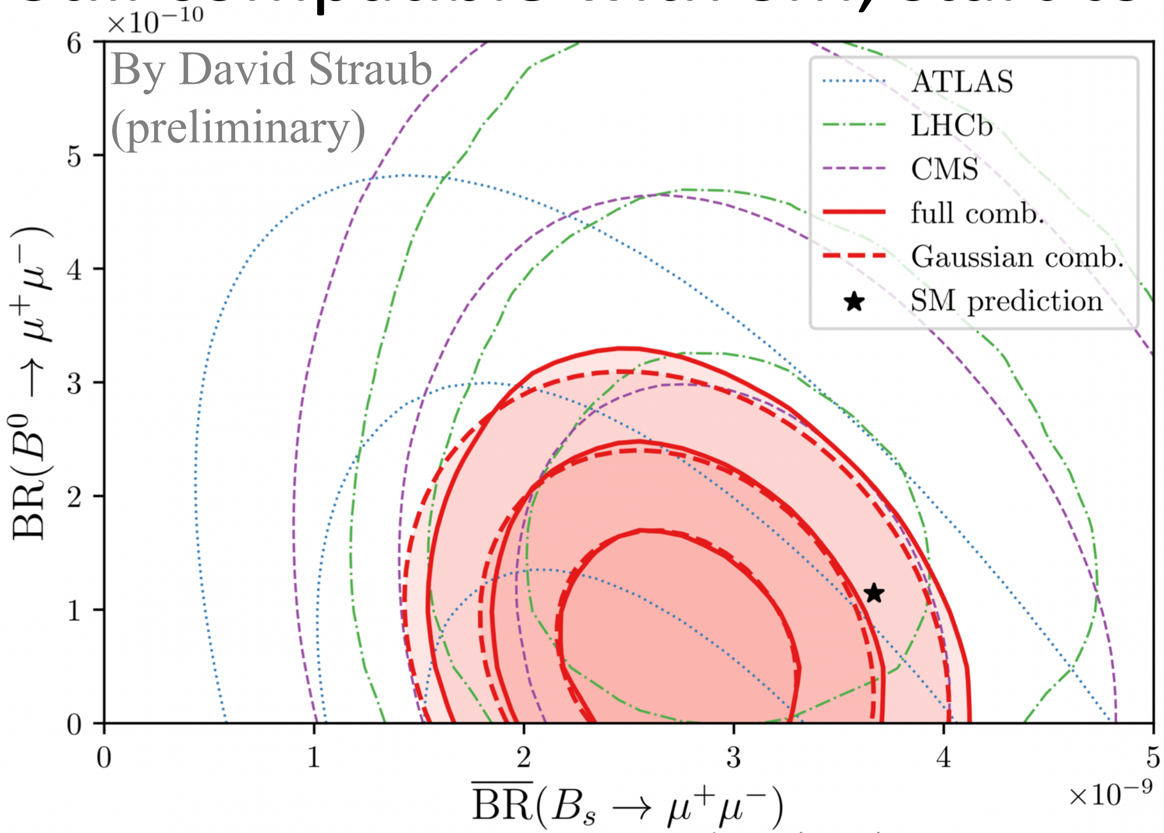
- Road to $B^0_{(s)} \to \mu^+\mu^-$



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

- $B^0_s \to \mu^+\mu^-$ observed in single experiment(s)

  LHCb (4.6 fb^{-1}): 7.8σ, ATLAS (26 fb^{-1}): 4.6σ, CMS (61 fb^{-1}): 5.6σ
- Still compatible with SM, start to be interesting



[LHCb, PRL 118 (2017) 191801]
[ATLAS, JHEP 04 (2019) 098]
[CMS, CMS-PAS-BPH-16-004]

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

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

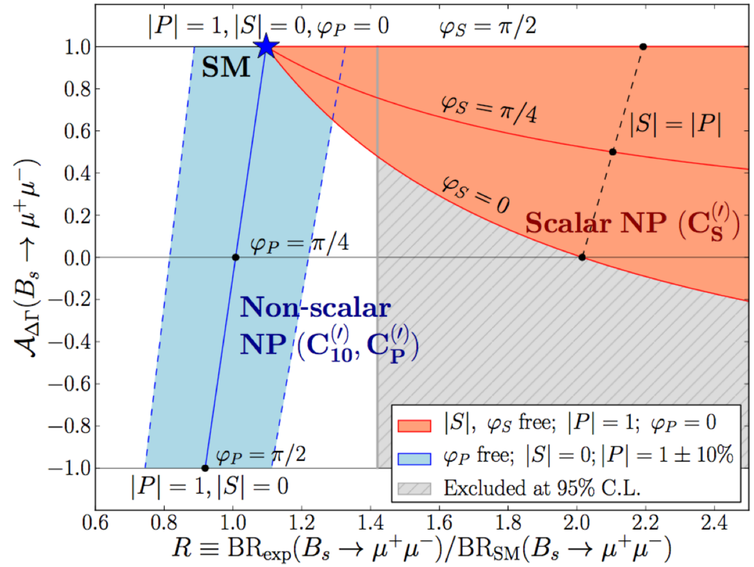
- First measurement, not yet sensitive to $A_{\Delta\Gamma}$

[PRL 118 (2017) 191801]

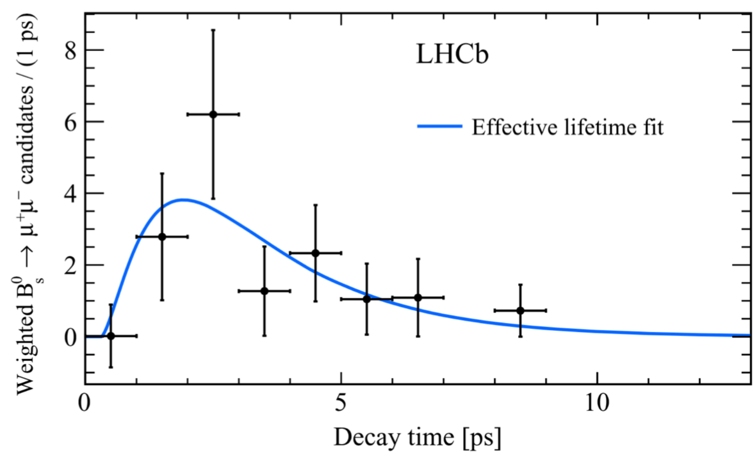
$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

$$1.70^{+0.61}_{-0.44} \text{ ps}$$

[CMS-PAS-BPH-16-004]



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



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

[arXiv:1905.06614]

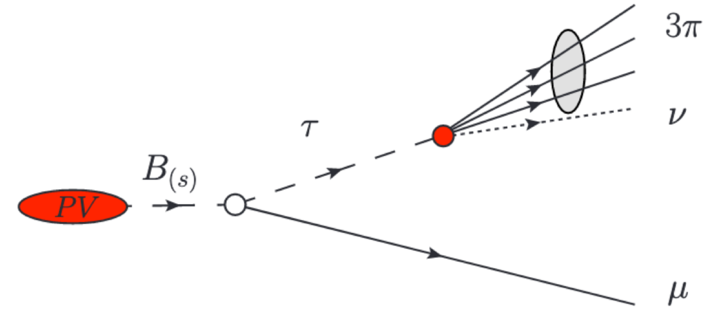
- LFV, highly suppressed in SM, $\mathcal{B} \sim O(10^{-54})$, may be enhanced by NP models
  - Z', up to 10^{-8}
  - Leptoquarks, $10^{-9} - 10^{-5}$
  - Pati-Salam gauge model, $10^{-4} - 10^{-6}$
- Best limit given by Babar

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

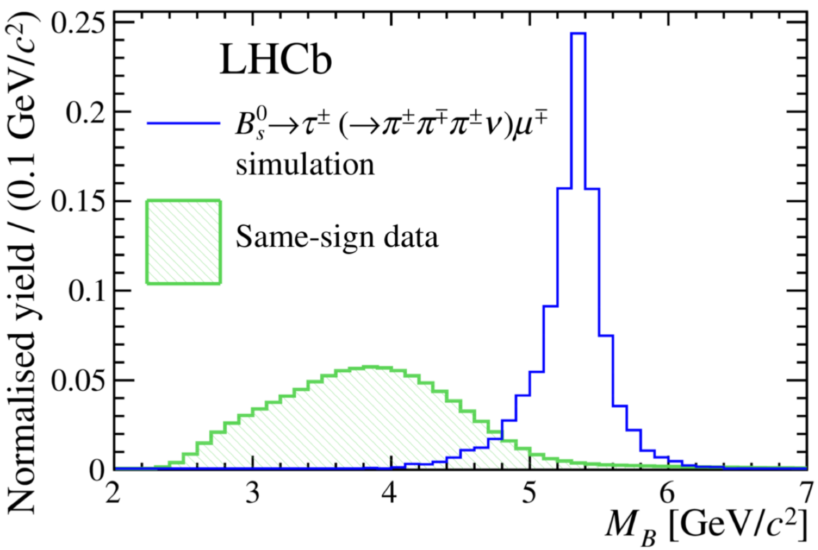
[Babar, PRD 77 (2008) 091104]

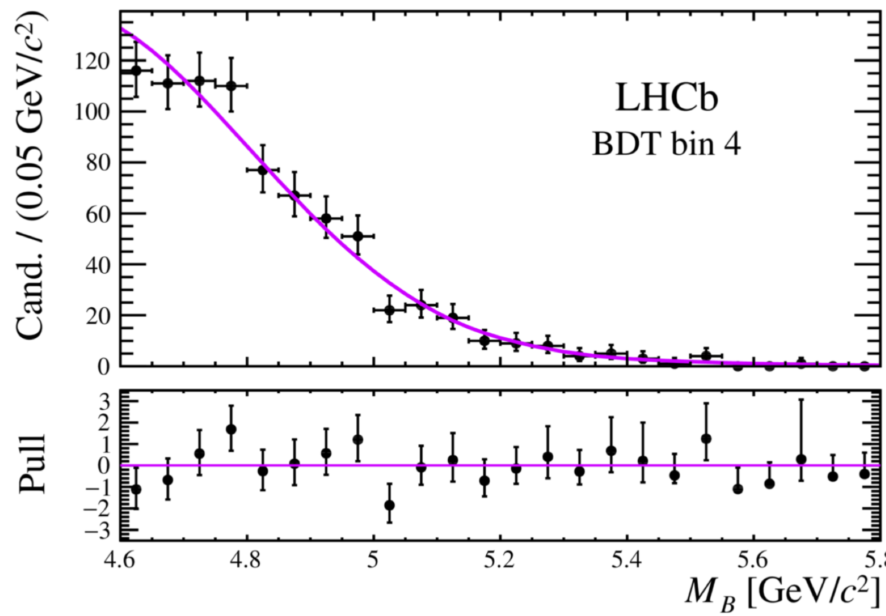
$B^0_{(s)} \to \tau^+\mu^-$

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



[arXiv:1905.06614]



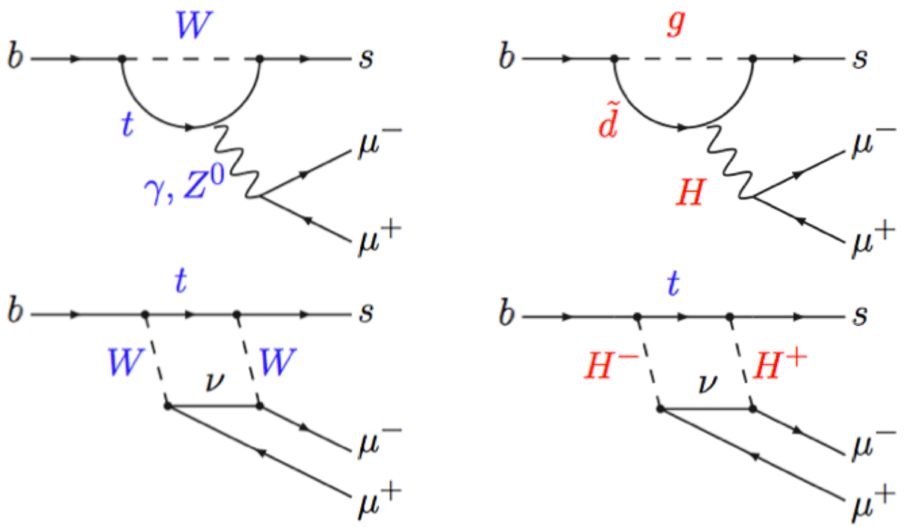


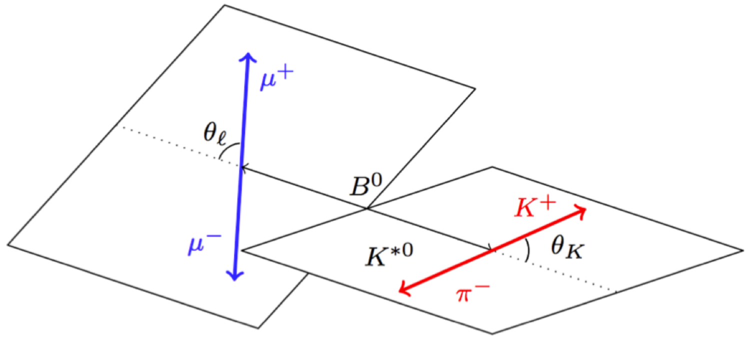
$\mathcal{B}(B^0 \to \tau^+\mu^-) < 1.4\times10^{-5}$ at 95% CL

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

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

- Rates and angular distributions sensitive to NP



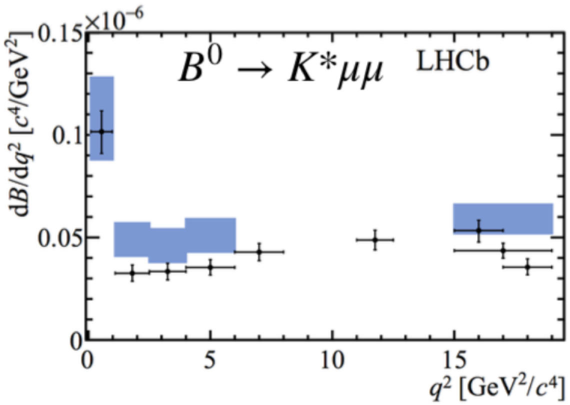


$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos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

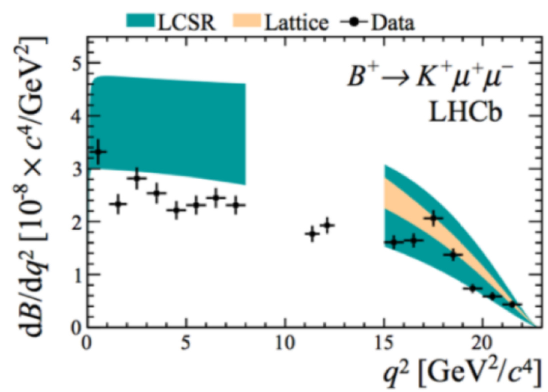
Branching fraction of $b \to s\ell^+\ell^-$

- Some tensions seen

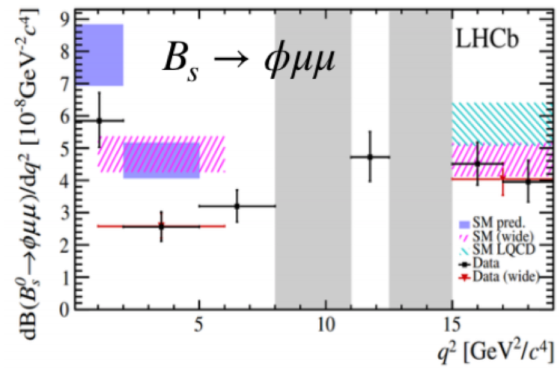
JHEP 11 (2016) 047



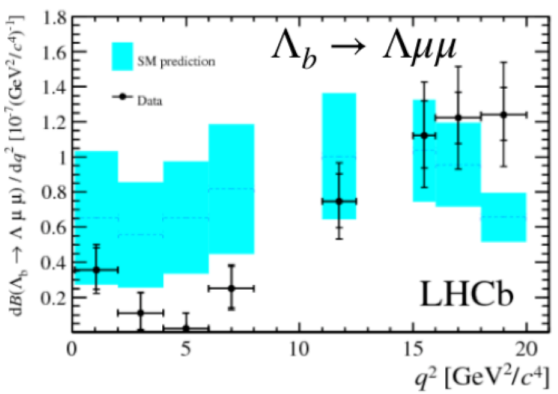
JHEP 06 (2014) 133



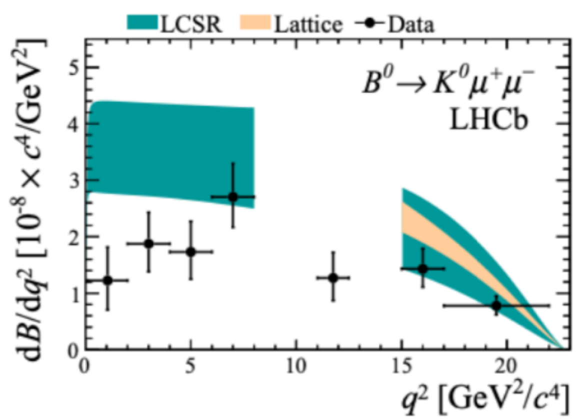
JHEP 09 (2015) 179



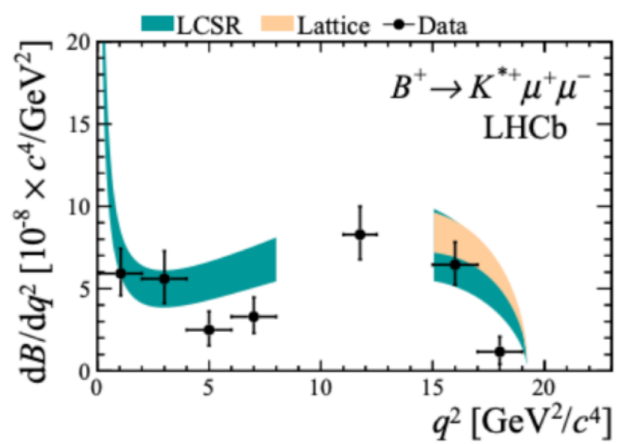
JHEP 06 (2015) 115



JHEP 06 (2014) 133

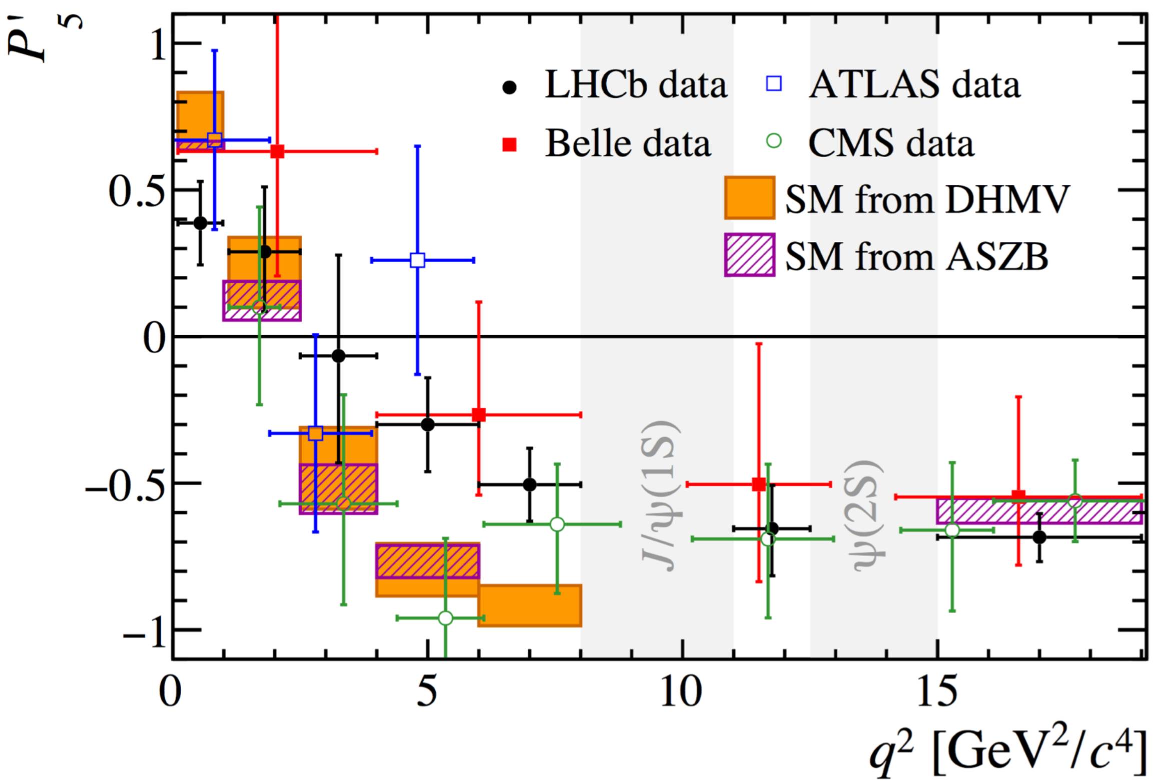


JHEP 06 (2014) 133



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

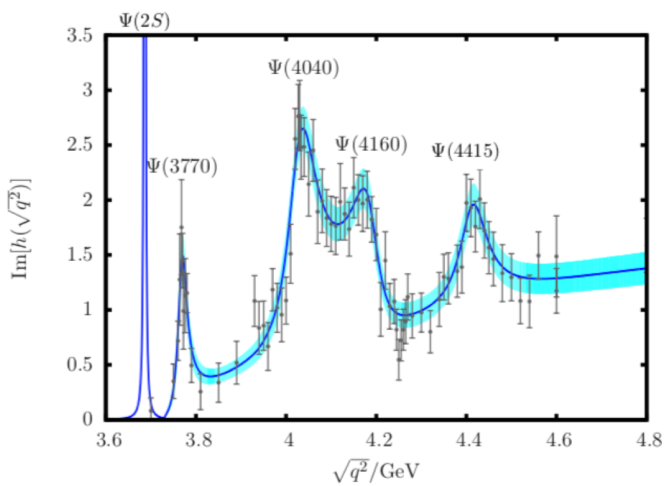
- $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$, less form-factor dependent
- Also measured by Belle, ATLAS, CMS

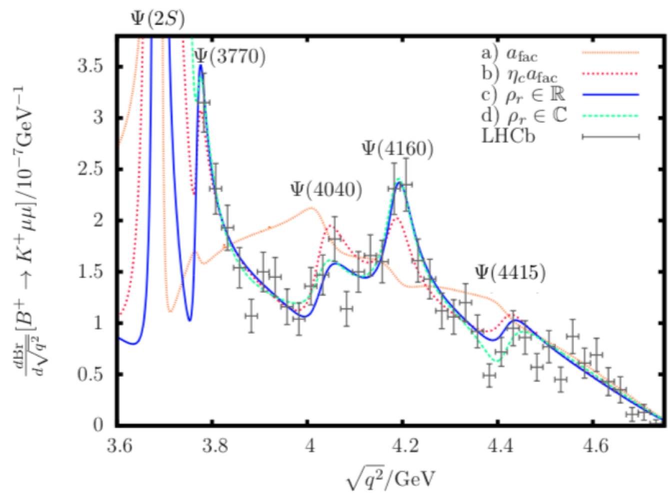


[LHCb, JHEP 02 (2016) 104]
[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

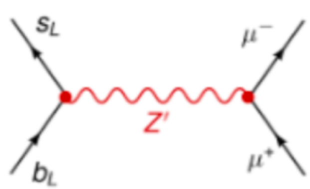
New physics, or QCD?

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

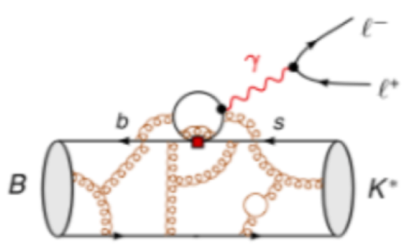




Optimist's view point

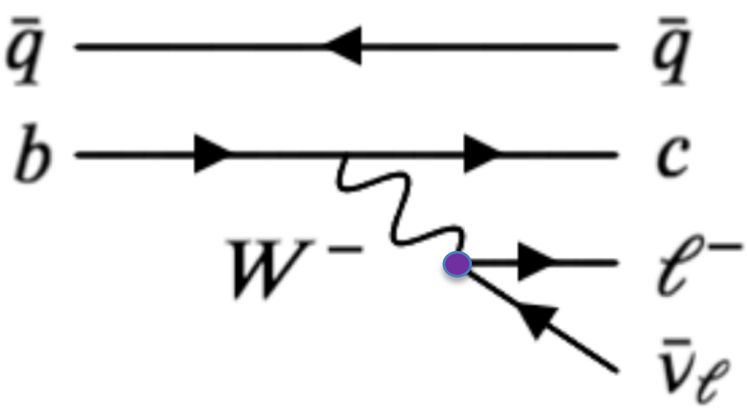


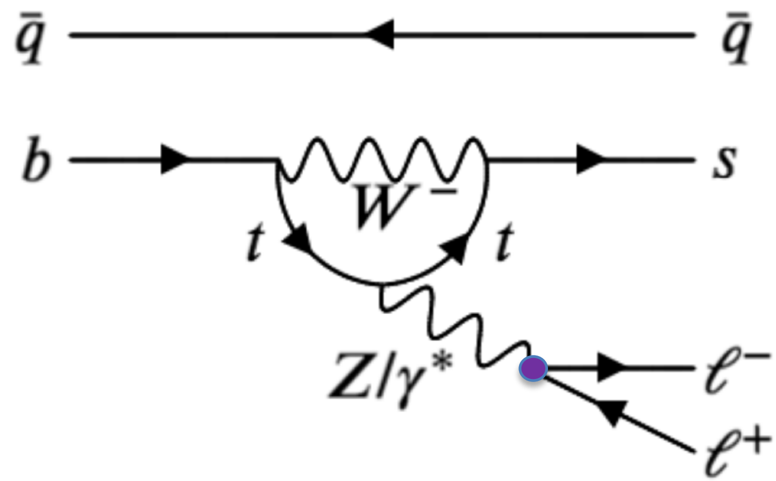
Pessimist's view point



Lepton flavor universality

- Three lepton families (e, μ, τ) have identical couplings to the gauge bosons





  - which means, e.g.,

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1$$

- Lepton flavor universality violation? New Physics!

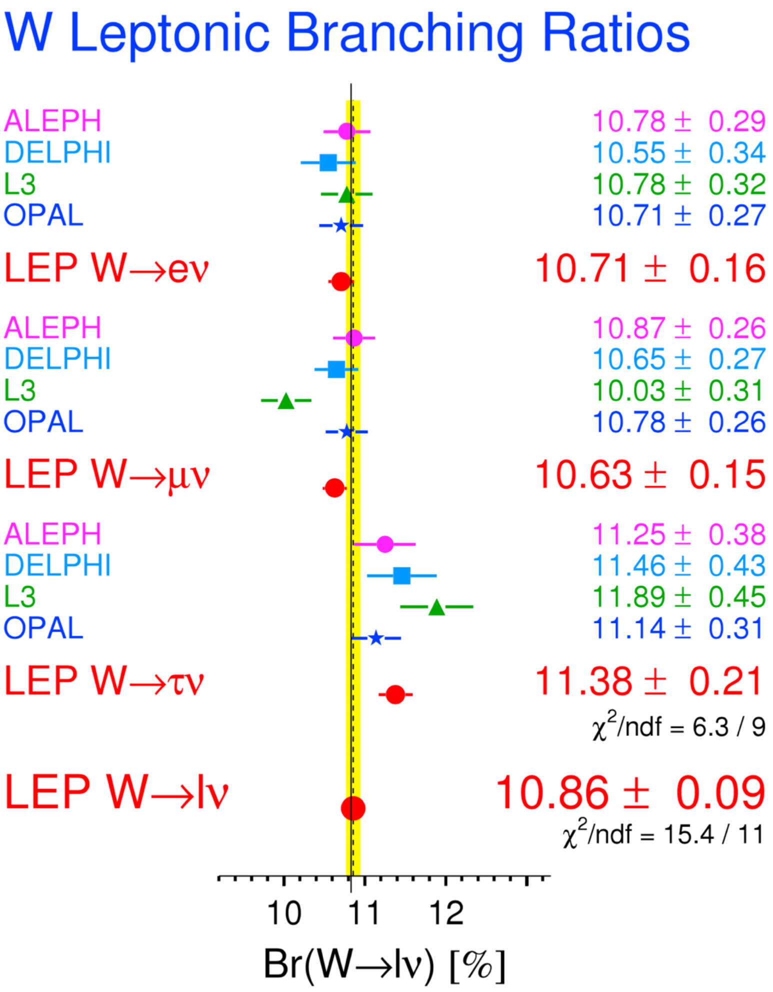
Experimental test of LFU

- Well established in SM, e.g. *W->lν*
  - Some tension

[LEP, PR 532 (2013) 119]

$$\mathcal{B}(W \to \mu\bar{\nu}_\mu)/\mathcal{B}(W \to e\bar{\nu}_e) = 0.993 \pm 0.019,$$
$$\mathcal{B}(W \to \tau\bar{\nu}_\tau)/\mathcal{B}(W \to e\bar{\nu}_e) = 1.063 \pm 0.027,$$
$$\mathcal{B}(W \to \tau\bar{\nu}_\tau)/\mathcal{B}(W \to \mu\bar{\nu}_\mu) = 1.070 \pm 0.026.$$

$$\frac{2\mathcal{B}(W\to\tau\bar{\nu}_\tau)}{\mathcal{B}(W\to e\bar{\nu}_e)+\mathcal{B}(W\to\mu\bar{\nu}_\mu)} = 1.066 \pm 0.025\ (2.6\sigma)$$

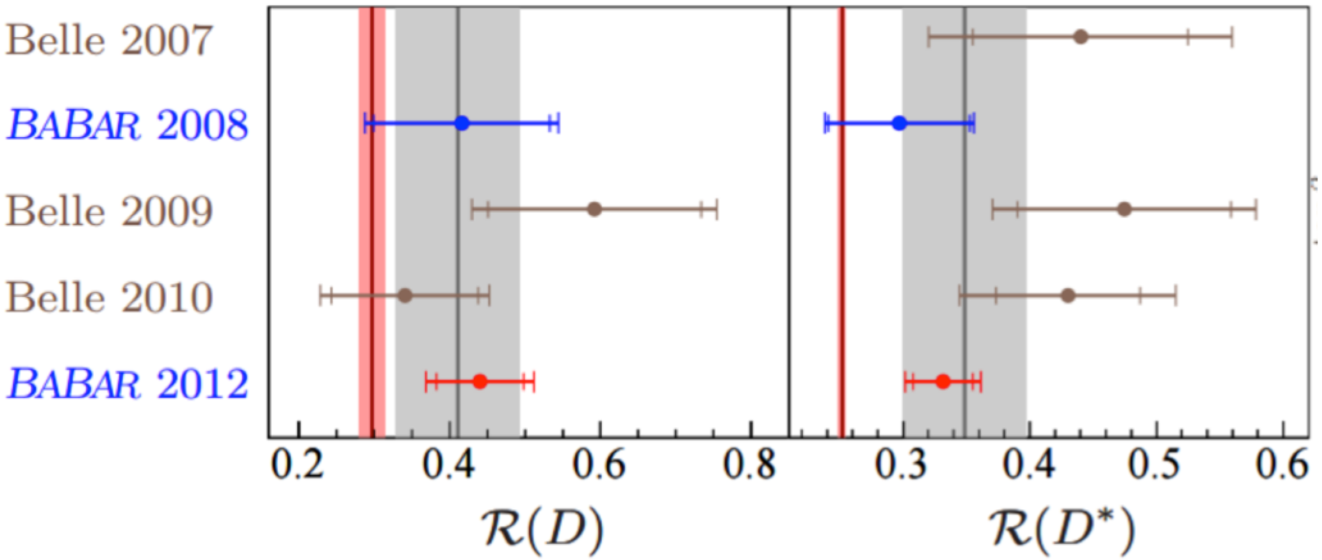


LFU in B system, pre-LHCb

- R(D$^{(*)}$), Babar reported deviation of ~3.2 σ

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

[Babar, PRD 88 (2013) 072012]



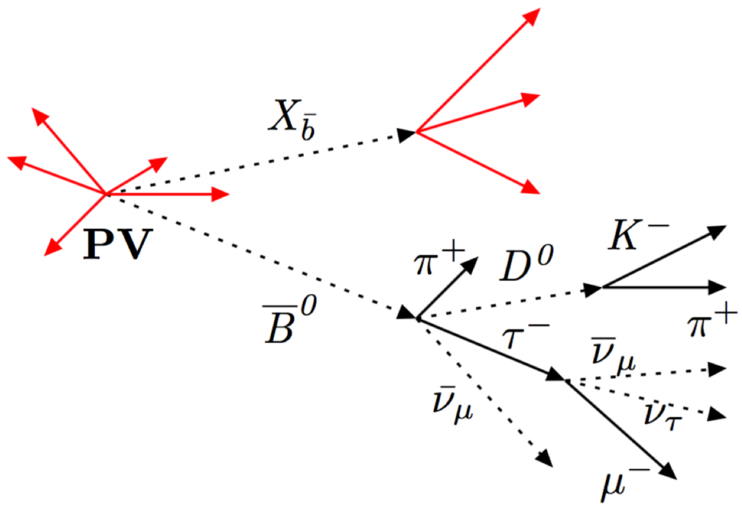
- No deviation seen in FCNC b->sll decays

R(D*) using munoic τ decays

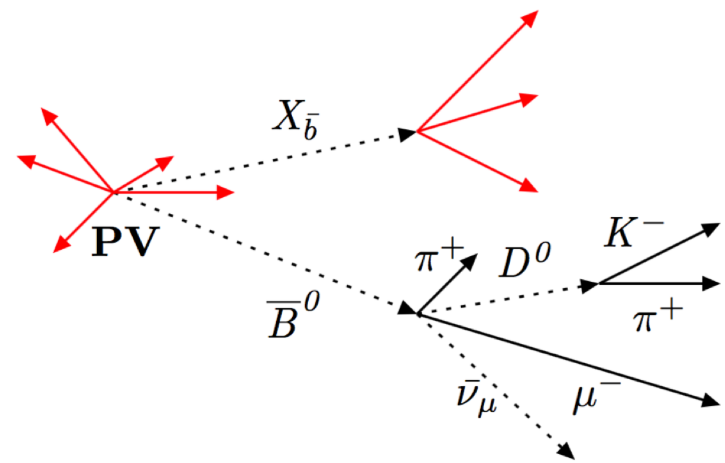
- Measure R(D*) using munoic τ decays
  - Pros: $\mathcal{B}$(τ->μX)~17.4%, B vertex rec'ible
  - Cros: no τ vertex

[PRL 115 (2015) 118003]

Signal $(B^0 \to D^{*+}\tau^-\overline{\nu}_\tau)$



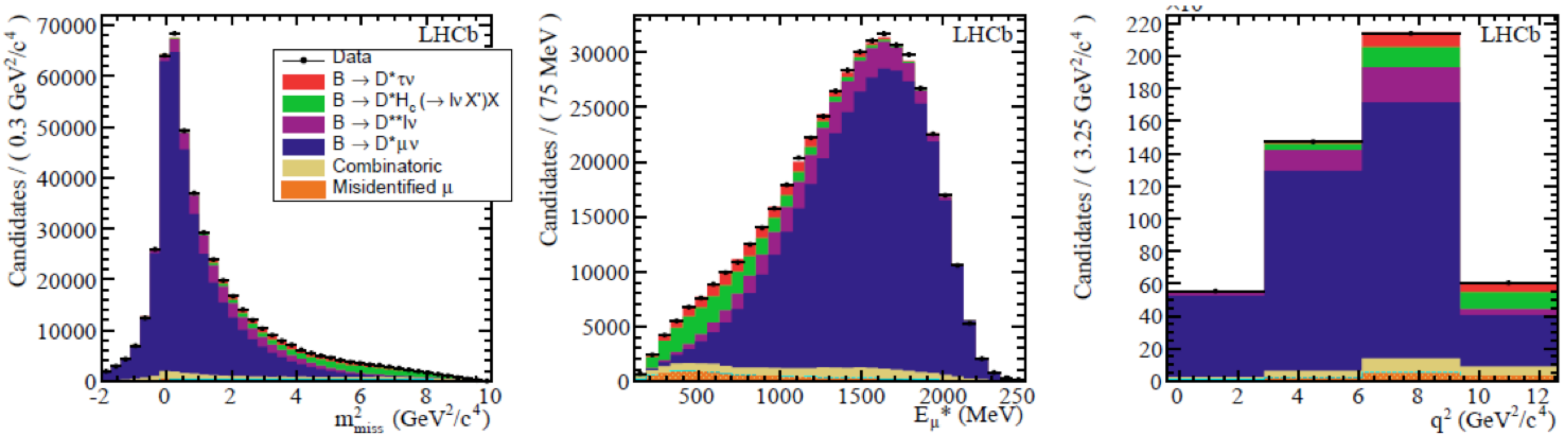
Normalisation $(B^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$



R(D*), results

- 3D fits, $\mathcal{R}_{D^*} = 0.336 \pm 0.027 \pm 0.030$
  - Signal yields: 16 500 ± 1 670

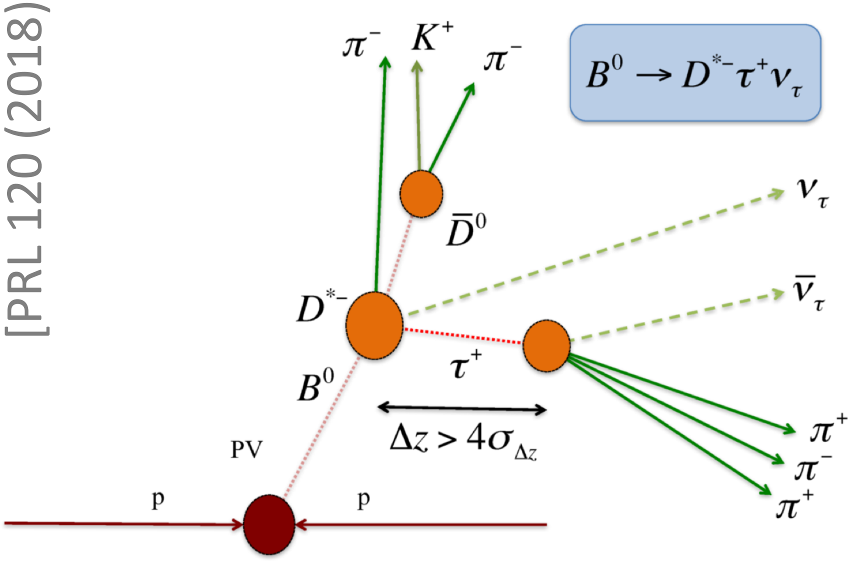
[PRL 115 (2015) 118003]

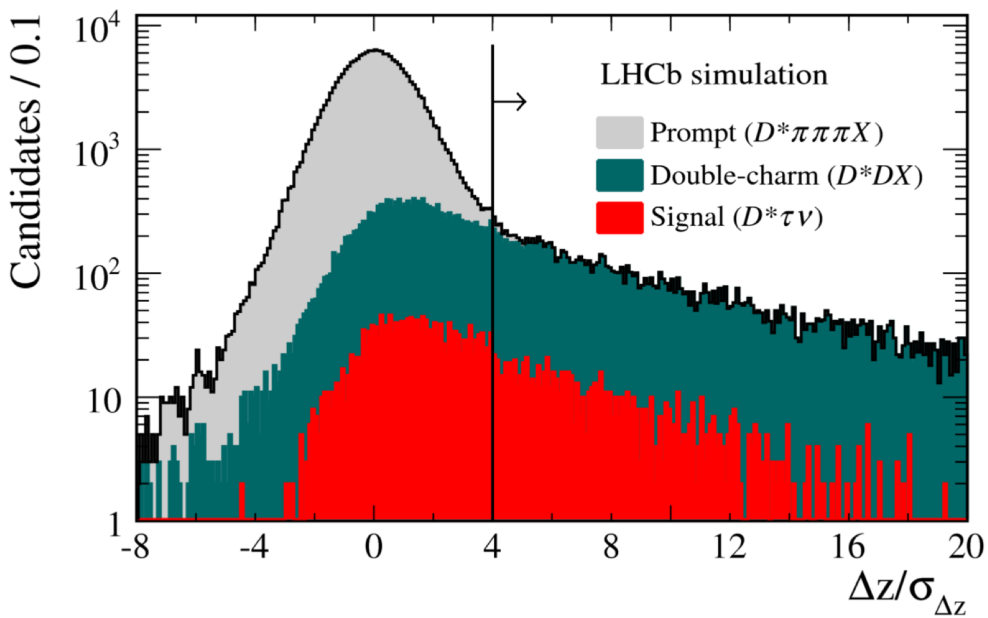


R(D*) using 3-prong τ decays

- Measure R(D*) using 3-prong τ decays
  - Pros: $\mathcal{B}(\tau \to 3\pi^{\pm}X)$~9%+4%($\geq 1\pi^0$), B/τ vertex rec'ible
  - Cros: soft $\pi^{\pm}$, bkg; different from norm. decay

[PRL 120 (2018) 171802]





R(D*), results

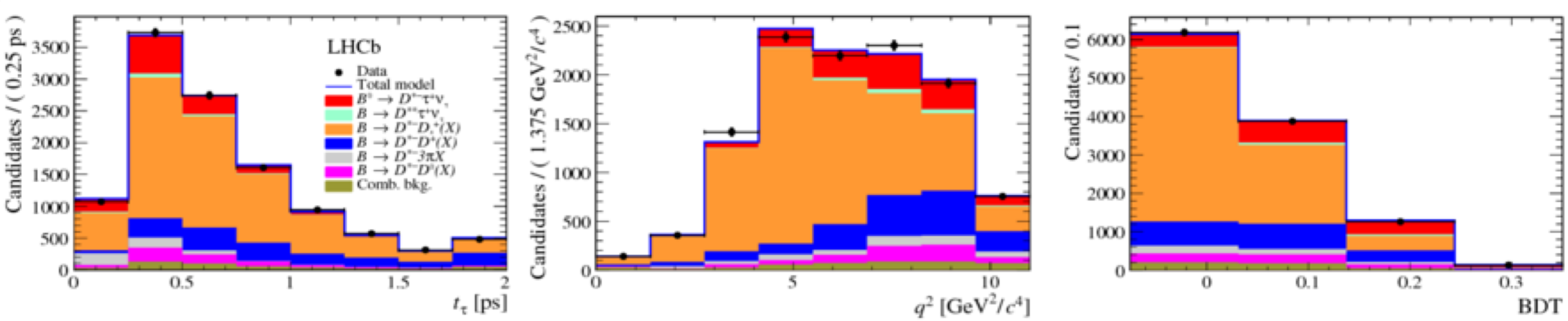
- Normalized to $B^0 \to D^{*-}3\pi$

$$R_{had}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)} \qquad R(D^*) = R_{had}(D^*) \times \frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^-\nu_\mu)}$$

- 3D fits, R(D*)=0.286 ± 0.019 ± 0.025 ± 0.021
  - Signal yields: 1273 ± 85

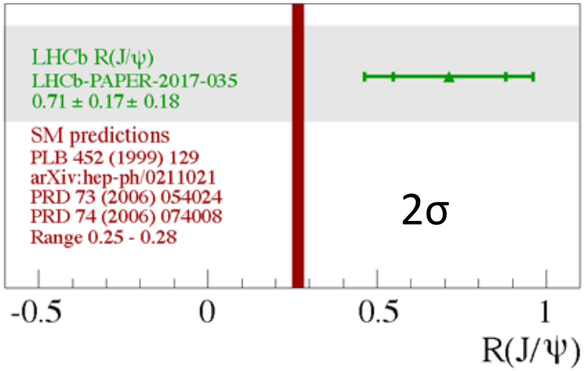
    c.f. muonic: 16 500 ± 1 670

[PRL 120 (2018) 171802]

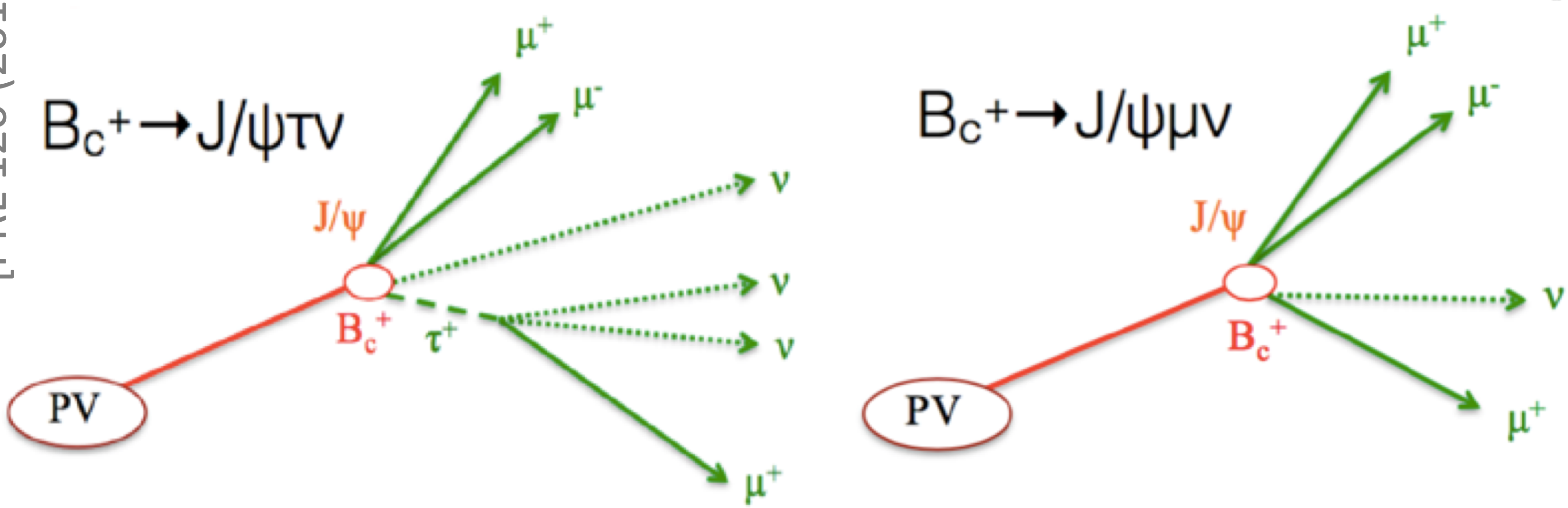


R(J/ψ) using munoic τ decays

- Measure R(J/ψ) using munoic τ decays
  - Pros: 3μ, $\mathcal{B}$(τ->μX)~17.4%
  - Cros: small $\sigma(B_c^+)$, no τ vertex
- Run-I, 1400 ± 300 signal (3σ)

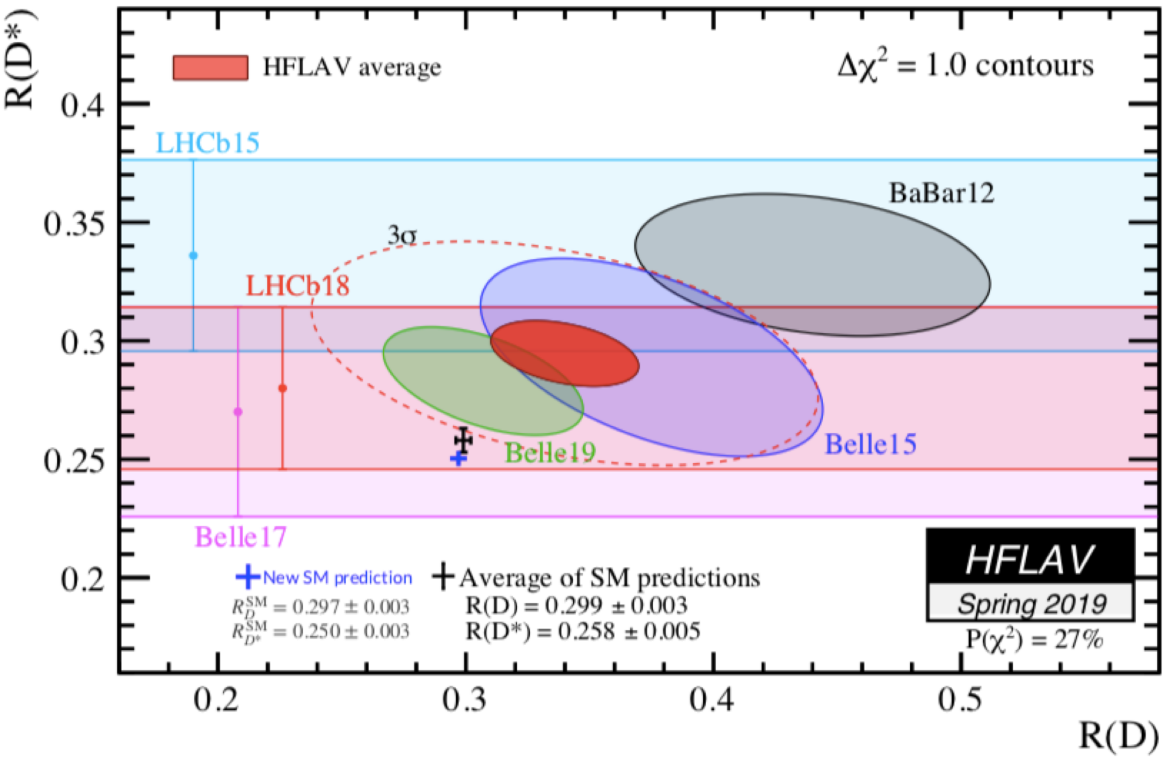


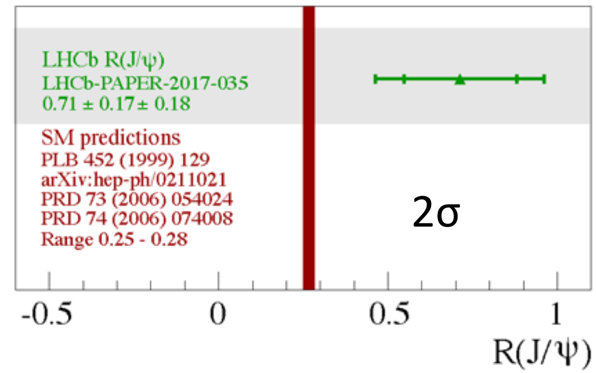
[PRL 120 (2018) 121801]



Summary of LFU in b->clv decays

- Deviations from SM seen by Babar/Belle/LHCb





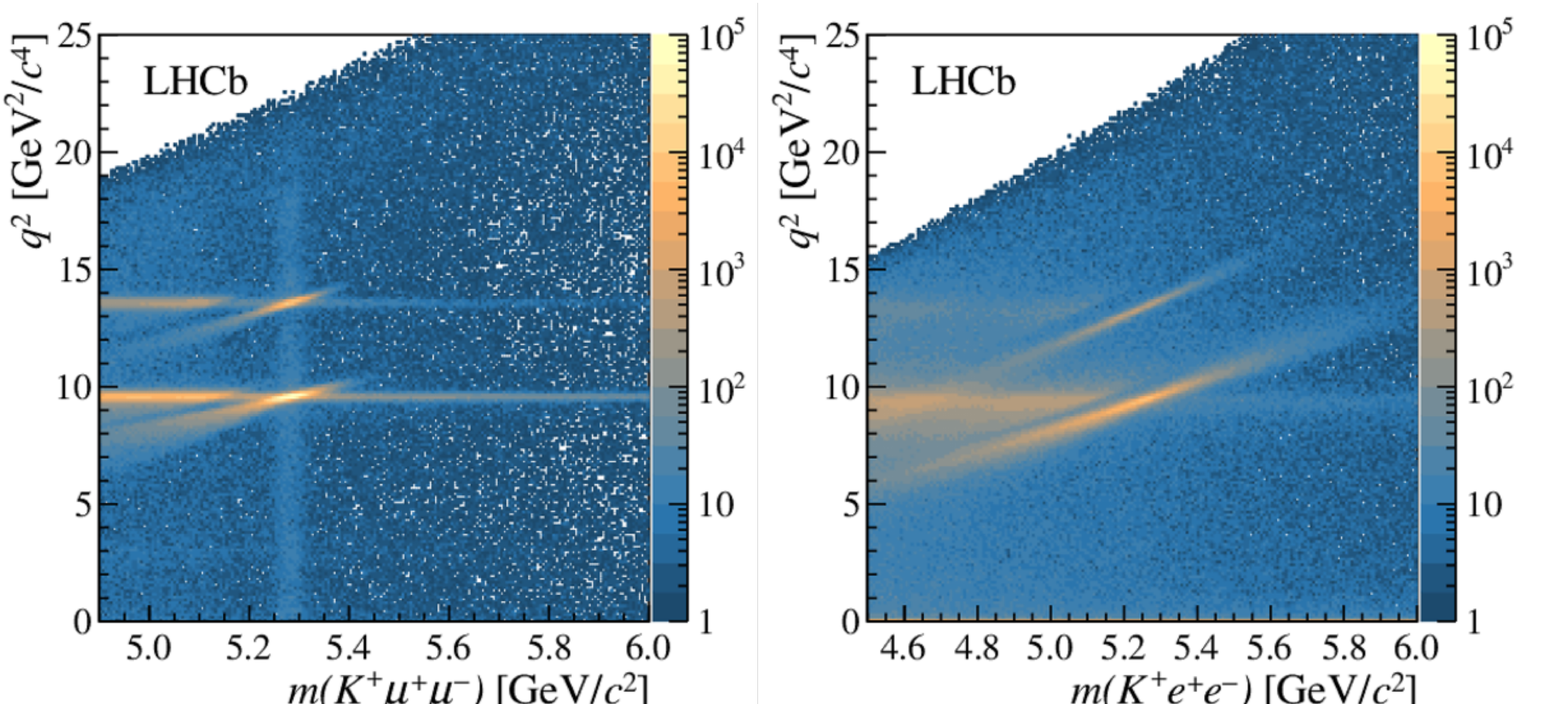
2σ

R(K), introduction

- Double ratio to control systematics

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

[PRL 122 (2019) 191801]

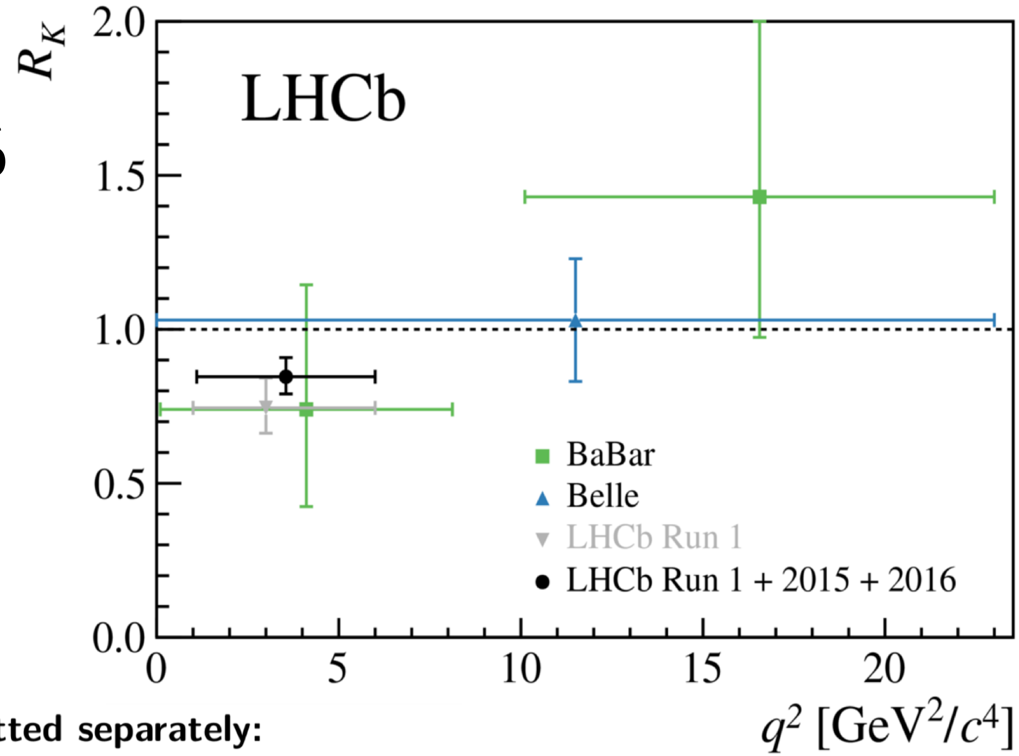


R(K), new results

- Include 2015+2016

$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$

$\sim 2.5\sigma$ from SM



[PRL 122 (2019) 191801]

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

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

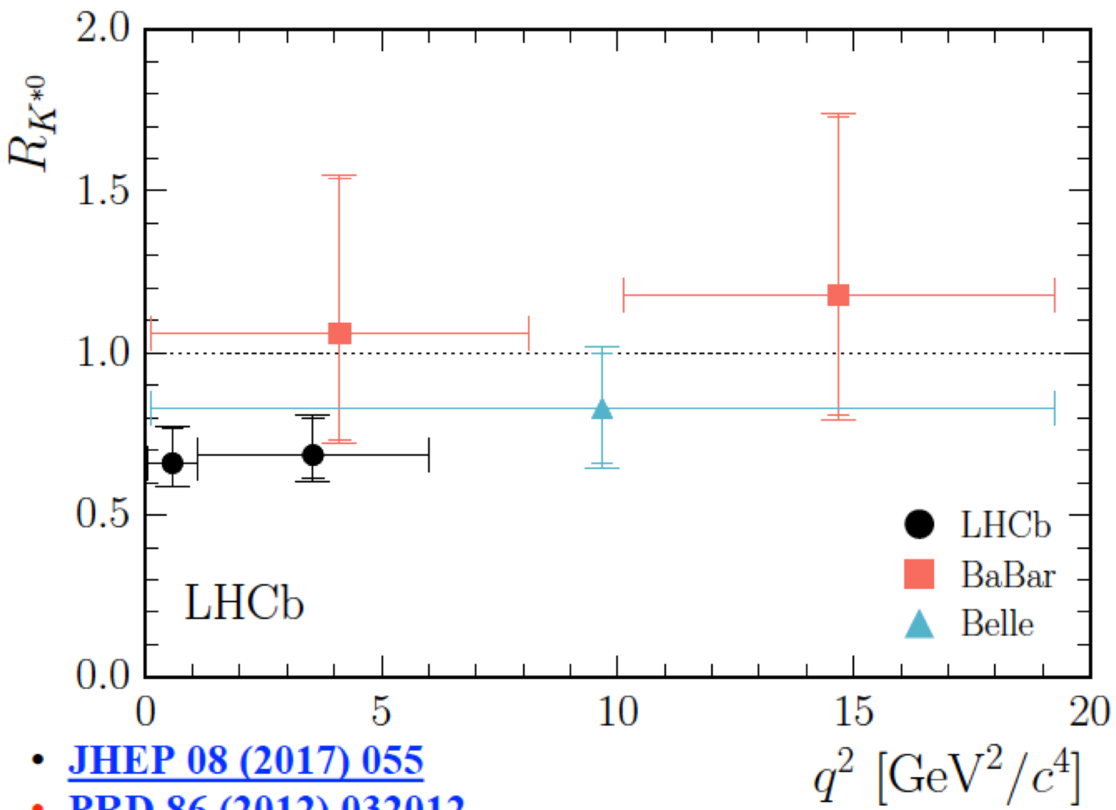
$$R^{\rm old}_{K\ \rm Run\ 1} = 0.745^{+0.090}_{-0.074} \pm 0.036$$ (PRL113(2014)151601) ,

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: $1.9\ \sigma$.

$R(K^{*0})$, 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

Prospects

- LHCb upgrades (2025: 23 fb^{-1}, Upgrade-II: 300 fb^{-1})

[CERN-LHCC-2018-027]

Observable	Current LHCb	LHCb 2025	Belle-II	LHCb Upgrade-II	ATLAS &CMS
$R_K(1 < q^2 < 6 \text{ GeV})$	0.1	0.025	0.036	0.007	
$R_{K^*}(1 < q^2 < 6 \text{ GeV})$	0.1	0.031	0.032	0.008	
R_ϕ, R_{pK}		0.08, 0.06		0.02, 0.02	
$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$	90%	34%		10%	21%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%	8%		2%	4%?
$R(D^*)$	0.026	0.0072	0.005	0.002	
$R(J/\psi)$	0.24	0.071		0.02	

Summary

- LHCb performed the world-leading measurements of rare decays and LFU:
  - Radiative, e.g., $B_s^0 \to \phi\gamma, \Lambda_b^0 \to \Lambda\gamma$
  - Rare strange, e.g., $K_S^0 \to \mu^+\mu^-$
  - Very rare decays, e.g., $B_{(s)}^0 \to \mu^+\mu^-$
  - LFV, e.g., $B_{(s)}^0 \to \tau^+\mu^-$
  - Electroweak penguin, e.g., $B^0 \to K^{*0}\mu^+\mu^-, \mathcal{R}_{K^{(*0)}}$
  - LFU in semi-leptonic decay, $\mathcal{R}_{D^*}$
- Your suggestions are always appreciated!