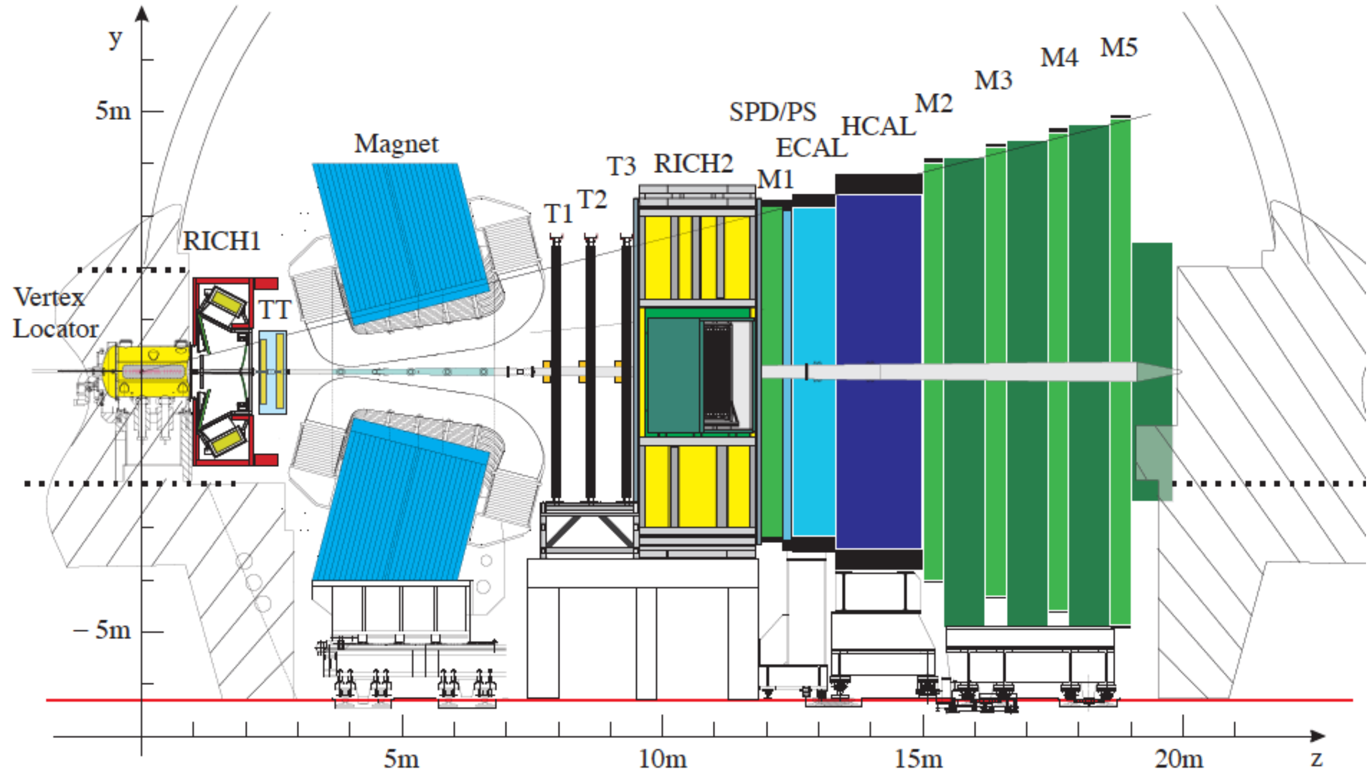
University of Chinese Academy of Sciences

Flavour anomalies at LHCb

何吉波 (Jibo HE)

第四届重味物理与量子色动力学研讨会
2022年7月27-30日

The LHCb experiment

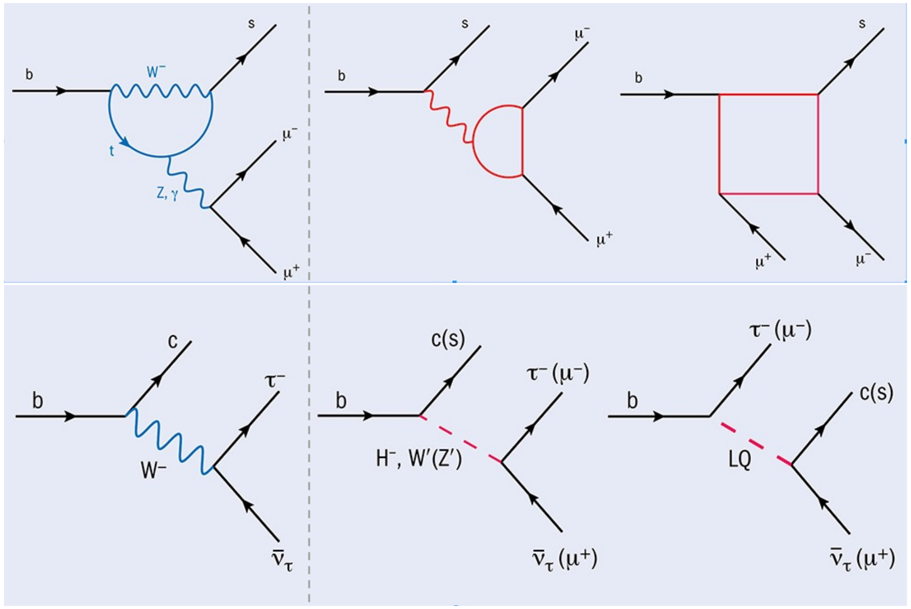


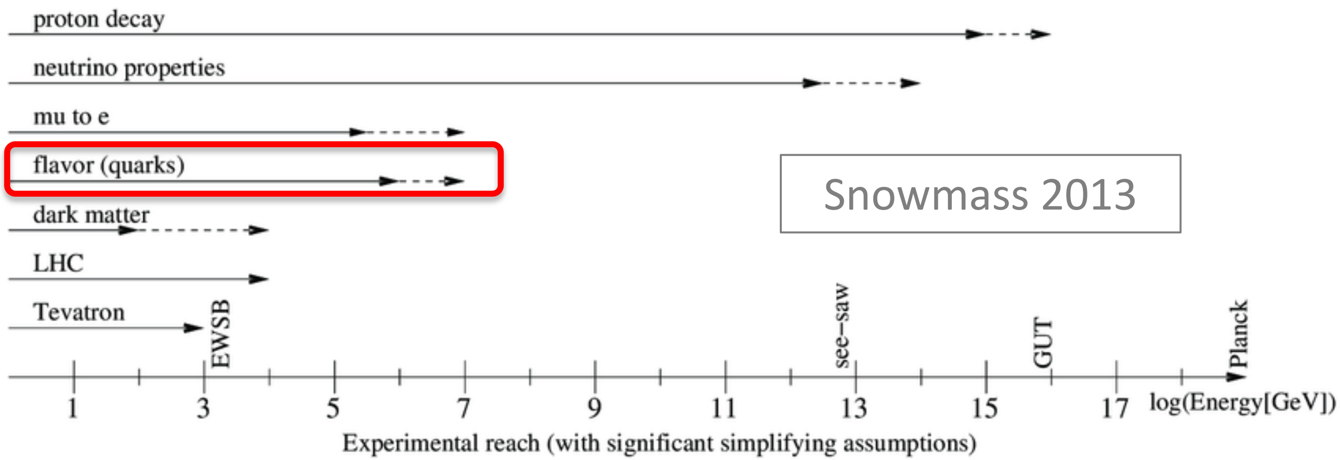
[JINST 3 (2008) S08005]

Vertex Locator	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking **(TT, T1-T3)**	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system **(M1-M5)**	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

Indirect search for New Physics

- Precision measurement of heavy hadron decays
  - Flavour-Changing NC
  - Flavour-Changing CC
- Probe New Physics at high energy scale

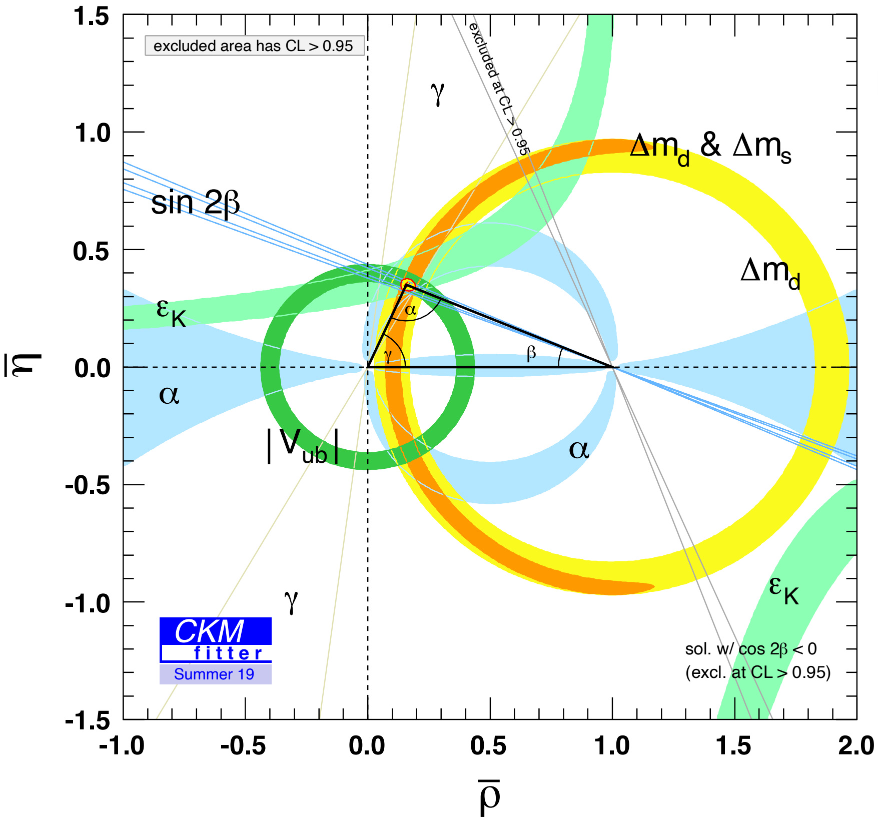


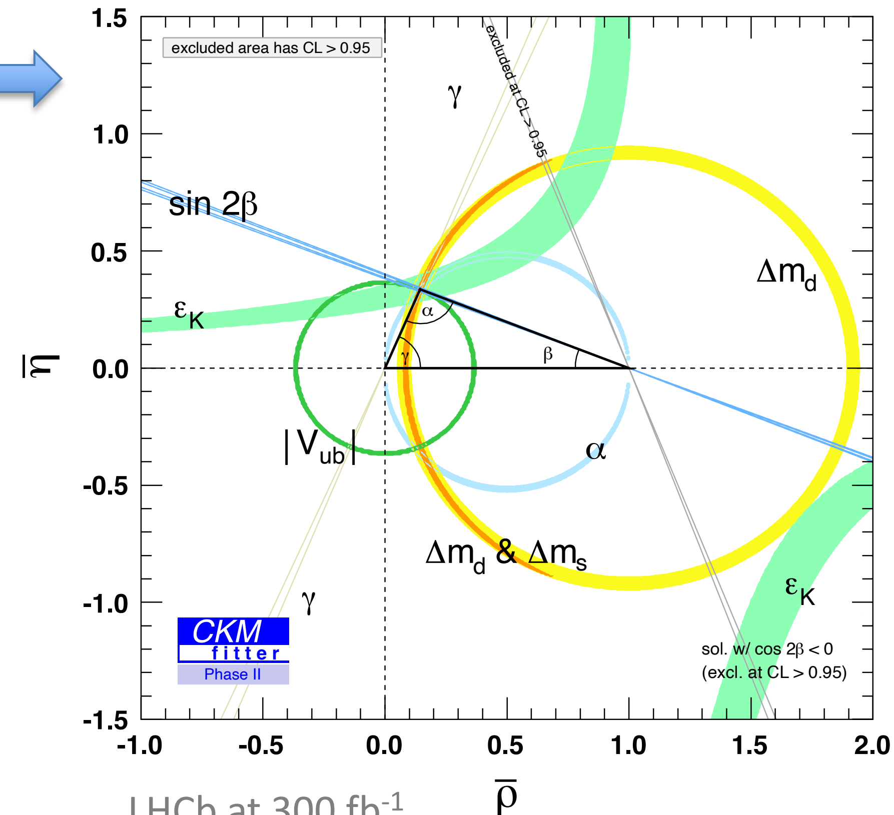


Snowmass 2013

Indirect search for NP (cont.)

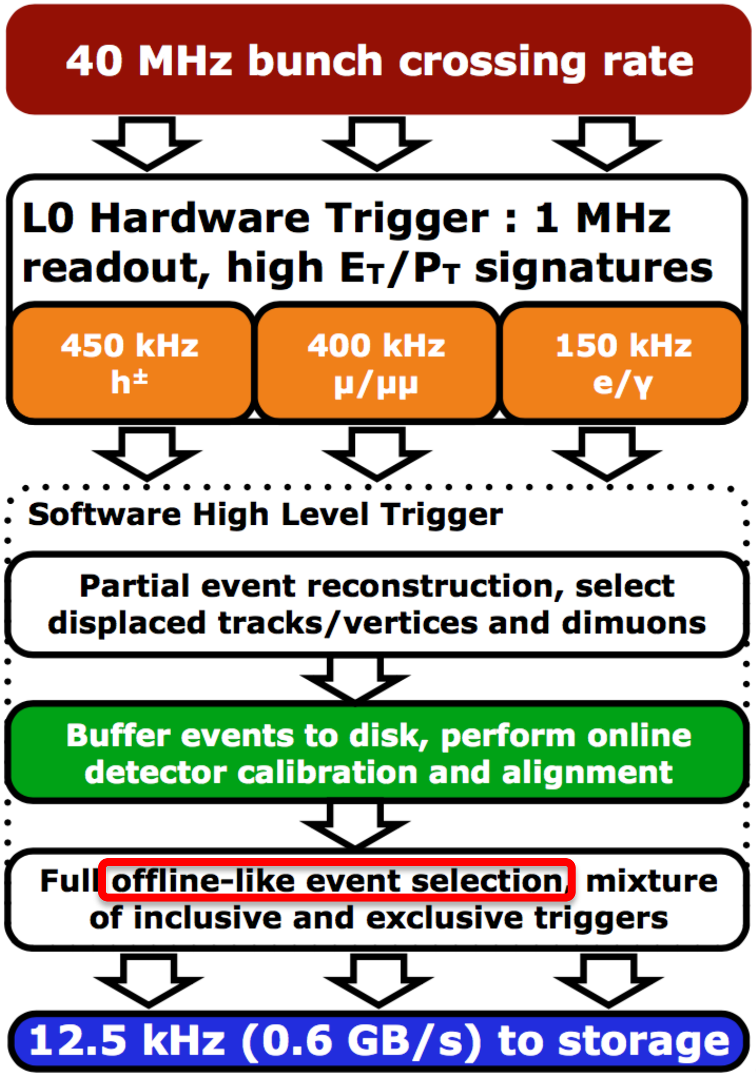
- Overconstrain the CKM triangle





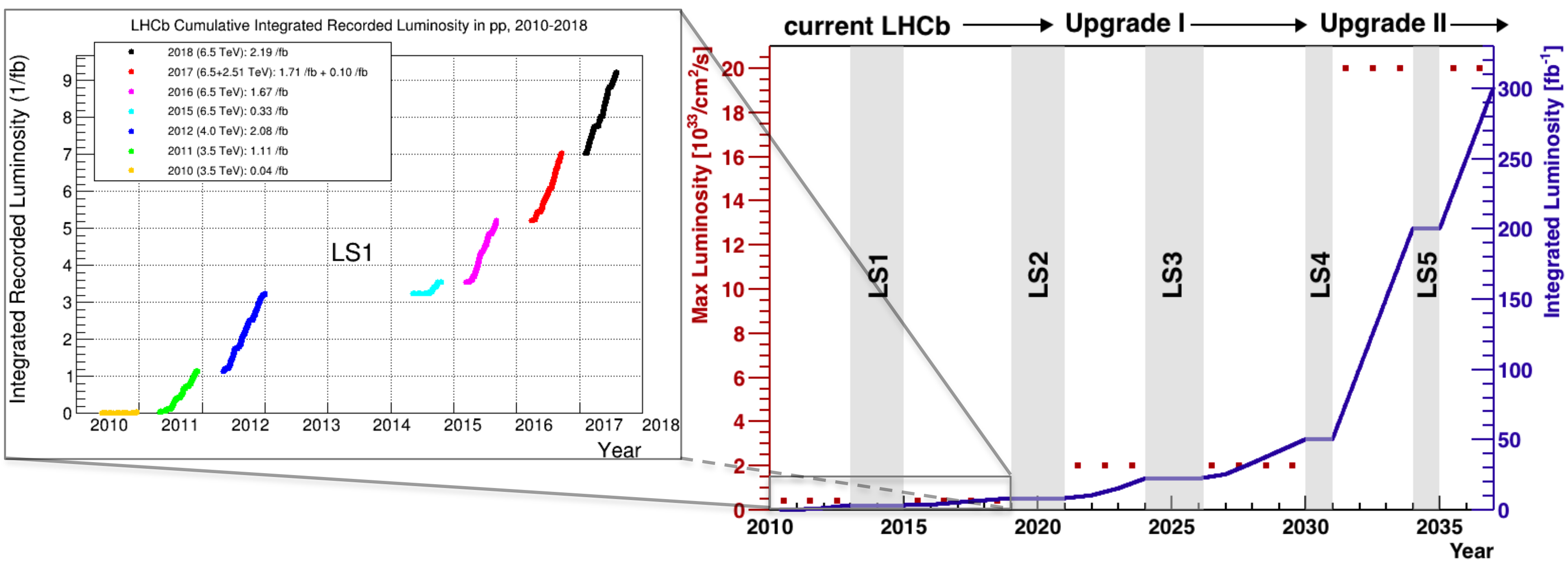
LHCb at 300 fb^{-1}, CMS/ATLAS at 3000 fb^{-1}, Belle II at 50 ab^{-1}.

The LHCb trigger (2018)



- L0, Hardware
  - $p_T(\mu_1)\times p_T(\mu_2) >$ (1.5 GeV)^2
  - $p_T(\mu) >$ 1.8 GeV
  - $E_T(e) >$ 2.4 GeV
  - $E_T(\gamma) >$ 3.0 GeV
  - $E_T(h) >$ 3.7 GeV
- High Level Trigger
  - Stage1, p_T, IP
  - Stage2, full selection

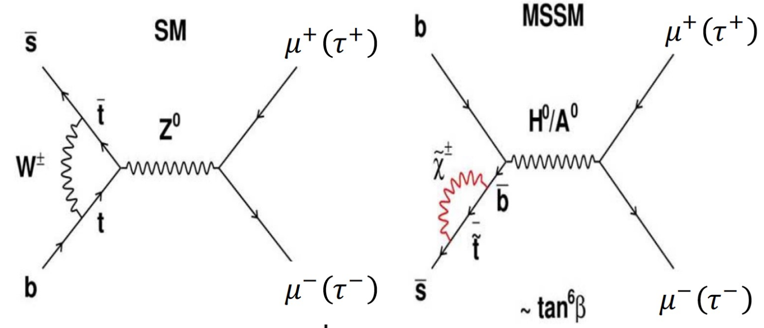
LHCb luminosity prospects



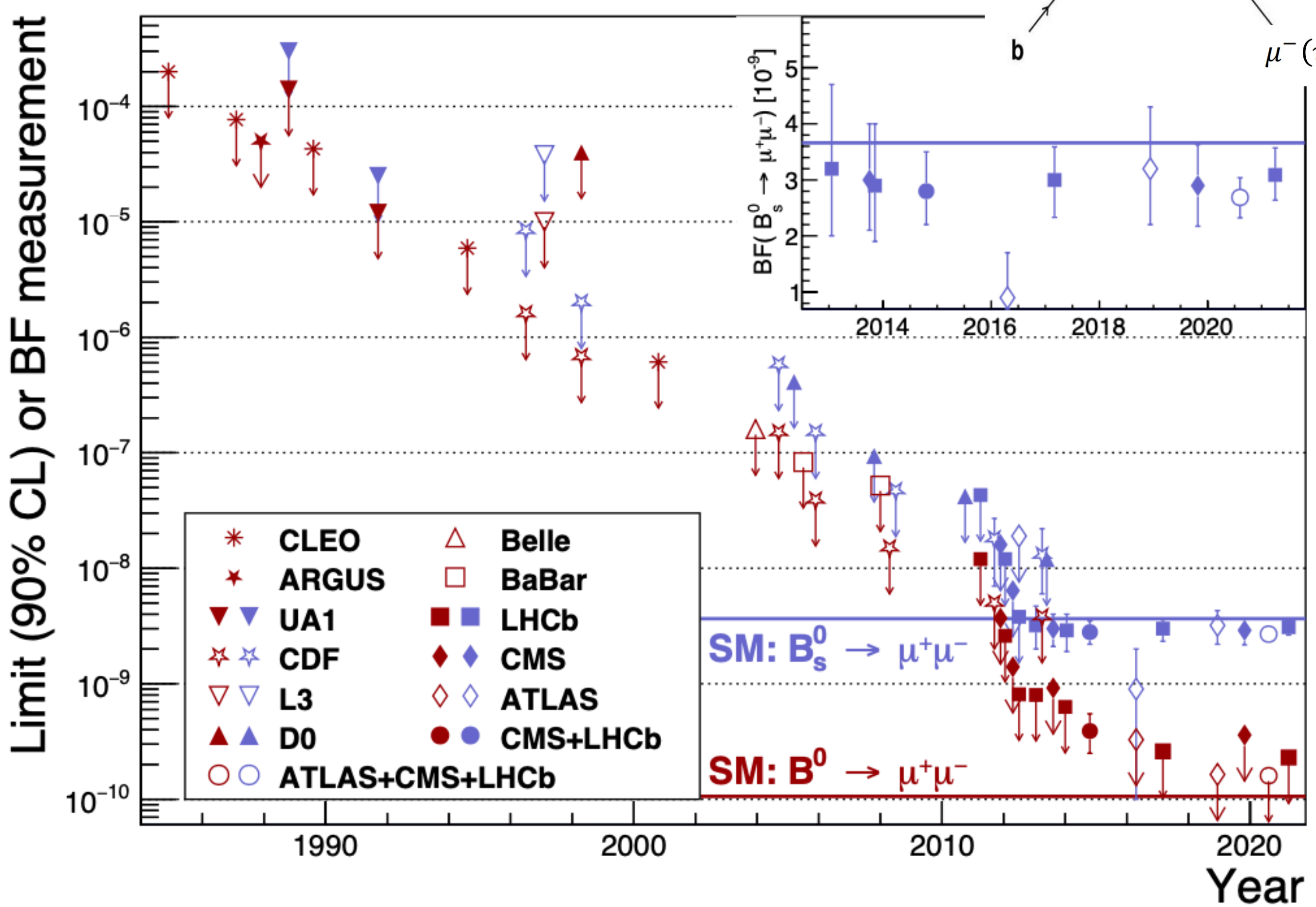
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2022-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??

Phase-1 Upgrade!! | **Phase-1b Upgrade!?** | **Phase-2 Upgrade??**

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



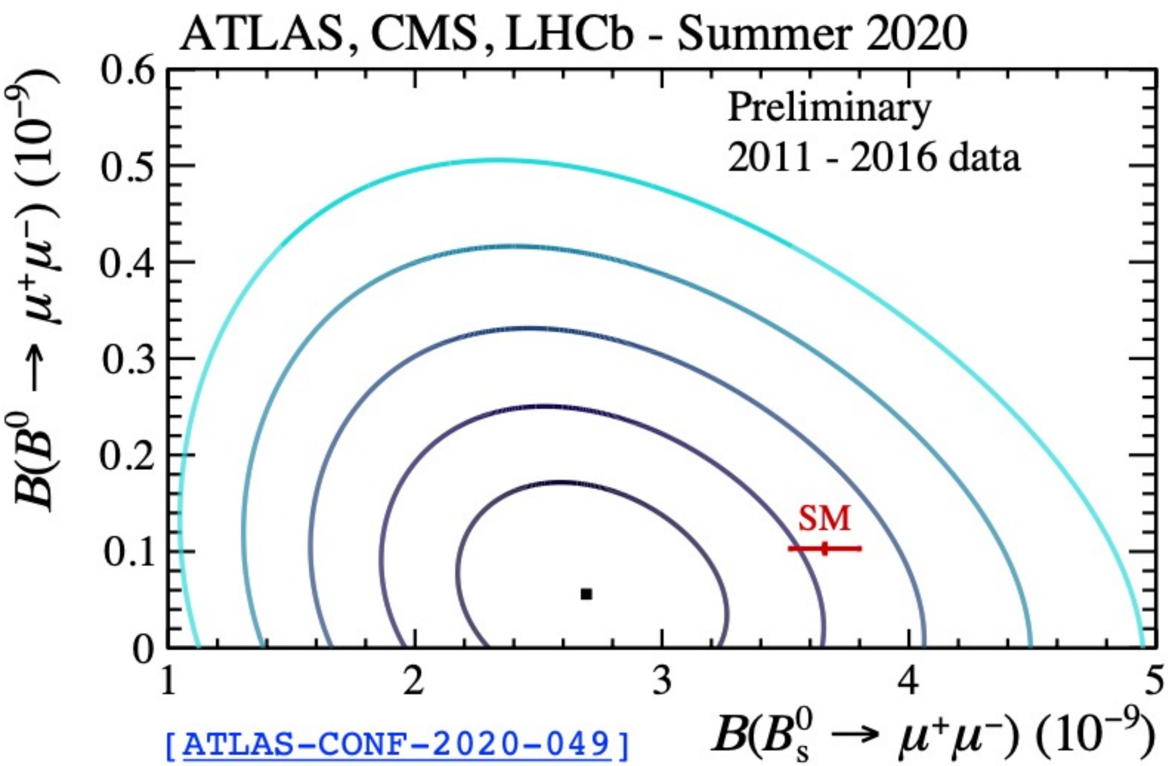
- Road to $B^0_{(s)} \to \mu^+\mu^-$



$B^0_{(s)} \to \mu^+\mu^-$, 2020 combination

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

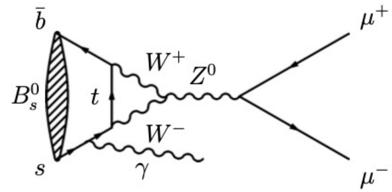
  LHCb (4.6 fb^{-1}): 7.8σ, ATLAS (26 fb^{-1}): 4.6σ, CMS (61 fb^{-1}): 5.6σ
- Still compatible with SM, room for NP?

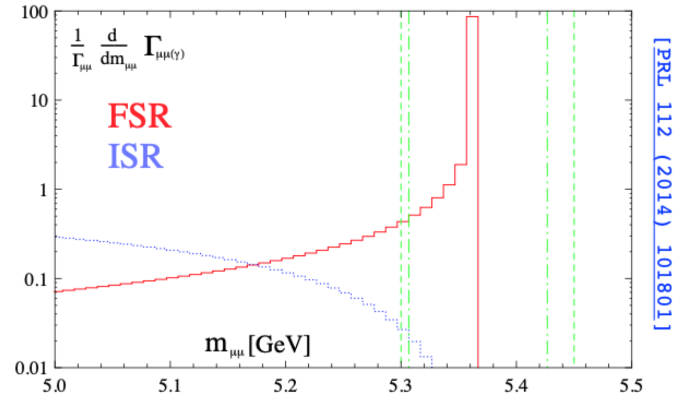


[ATLAS-CONF-2020-049]

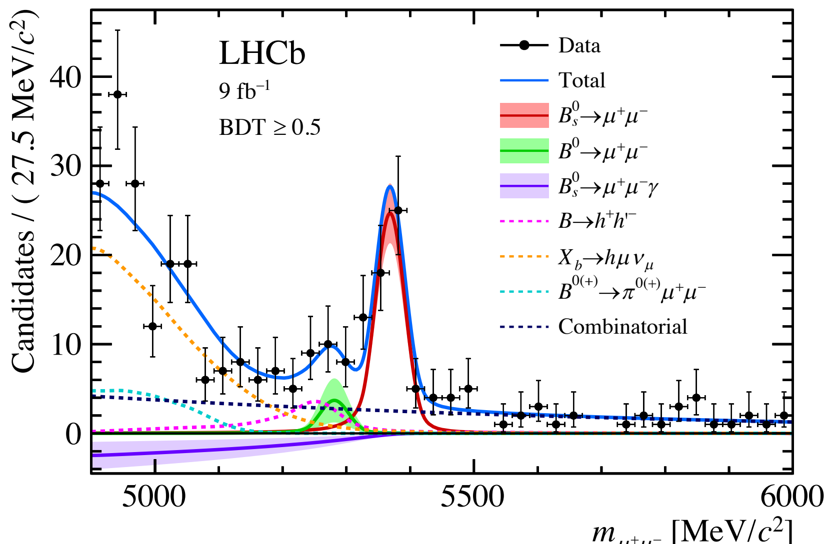
$B^0_{(s)} \to \mu^+\mu^-$ at LHCb

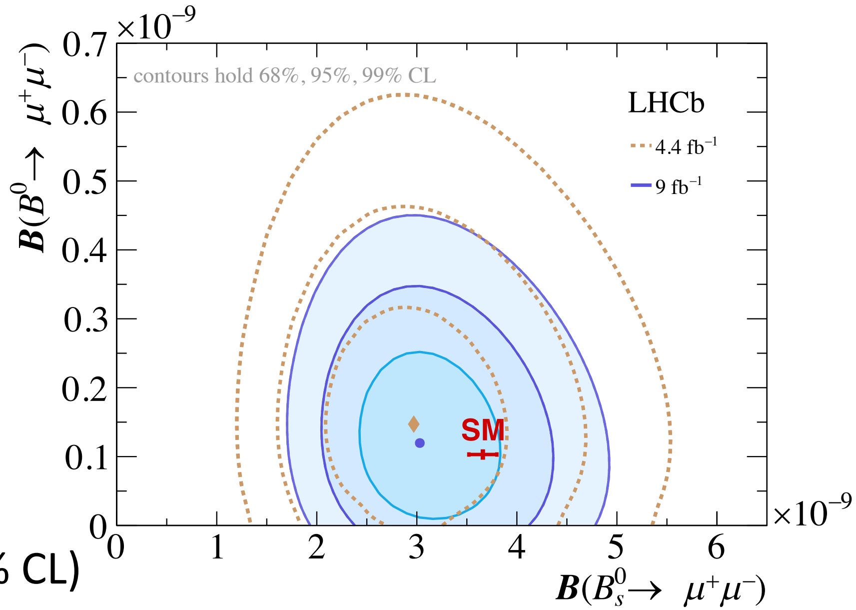
- Using all data, first limit on $B^0_s \to \mu^+\mu^-\gamma$





[PRL 128 (2022) 041801]





$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}\right)\times 10^{-9}$

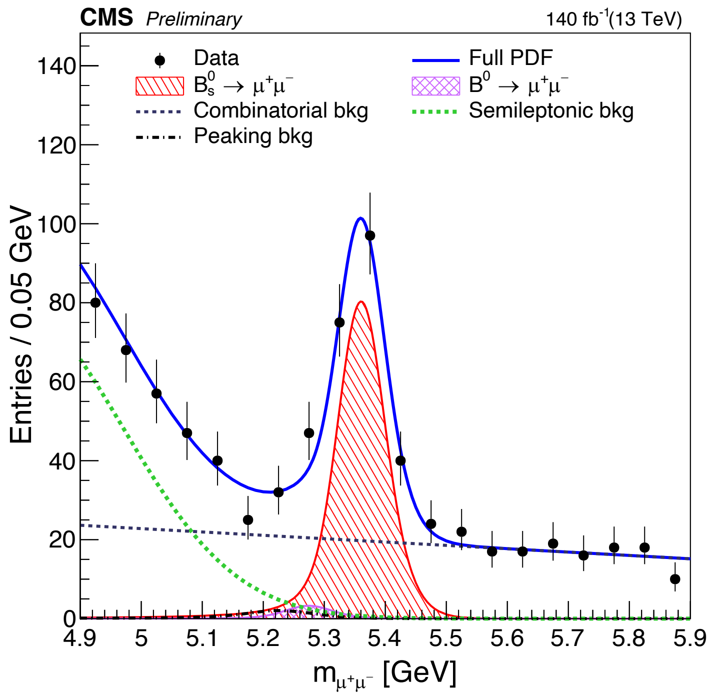
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6\times 10^{-10}$ (95% CL)

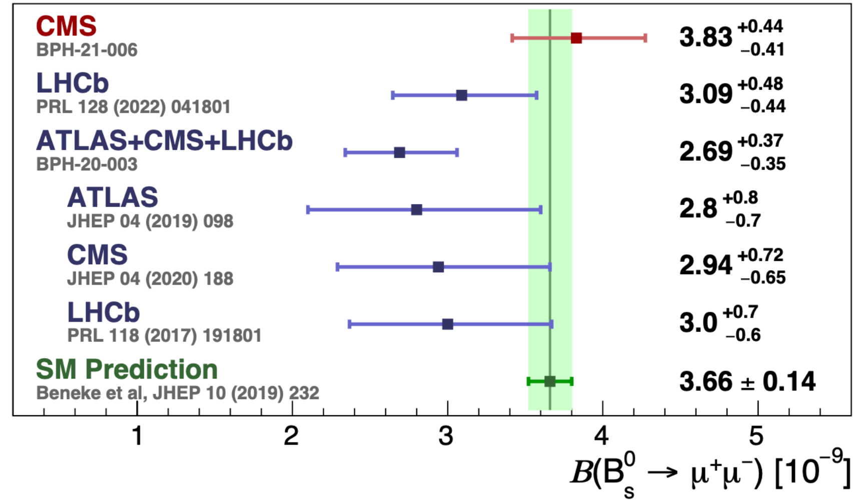
$\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m_{\mu^+\mu^-}>4.9\ \mathrm{GeV}} < 2.0\times 10^{-9}$ (95% CL)

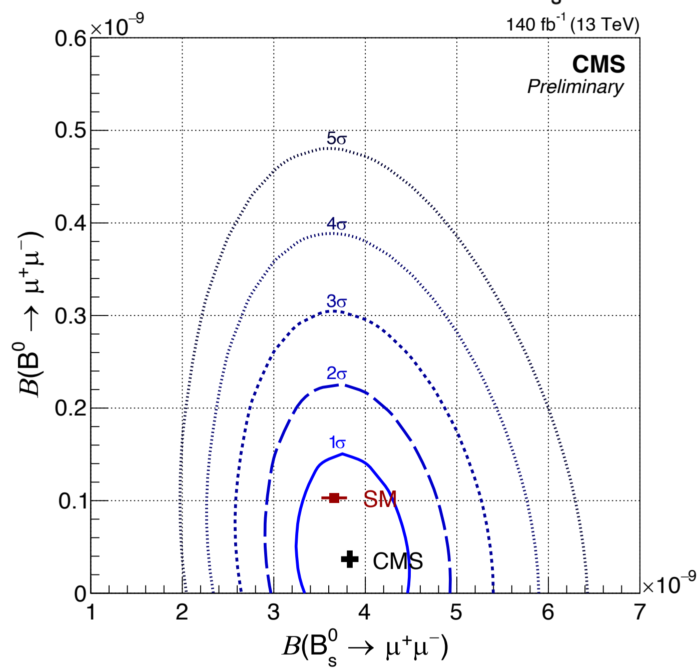
$B^0_{(s)} \to \mu^+\mu^-$ at CMS

- Using 2016-2018 data

[CMS PAS BPH-21-006]







$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.95^{+0.39}_{-0.37}{}^{+0.27}_{-0.22}{}^{+0.21}_{-0.19})\times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9\times 10^{-10} \text{ (95\% CL)}$$

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

[PRL 128 (2022) 041801]

- B_s^0 mixing ⇒ effective τ

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2A_{\Delta\Gamma}^{\mu^+\mu^-}y_s+y_s^2}{1+A_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right]$$

$$A_{\Delta\Gamma}^{\mu^+\mu^-} \equiv \frac{R_H^{\mu^+\mu^-}-R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-}+R_L^{\mu^+\mu^-}}$$

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

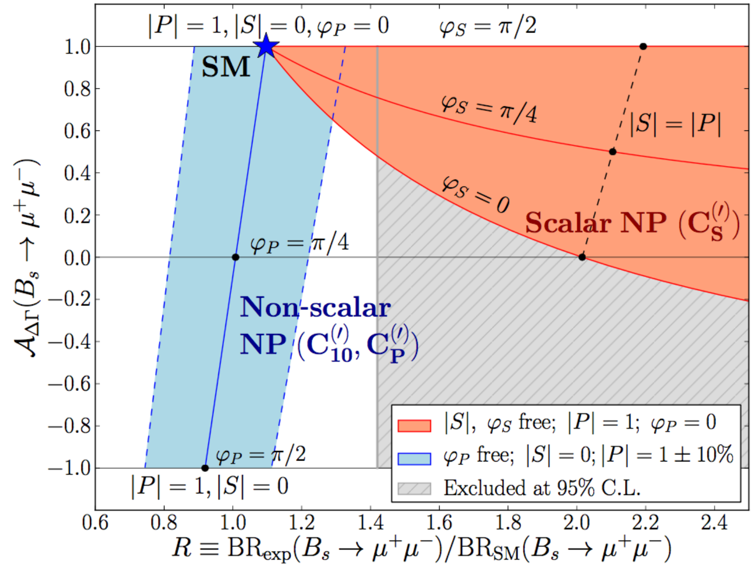
$$y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

- Measured by LHCb/CMS, not yet sensitive to $A_{\Delta\Gamma}$

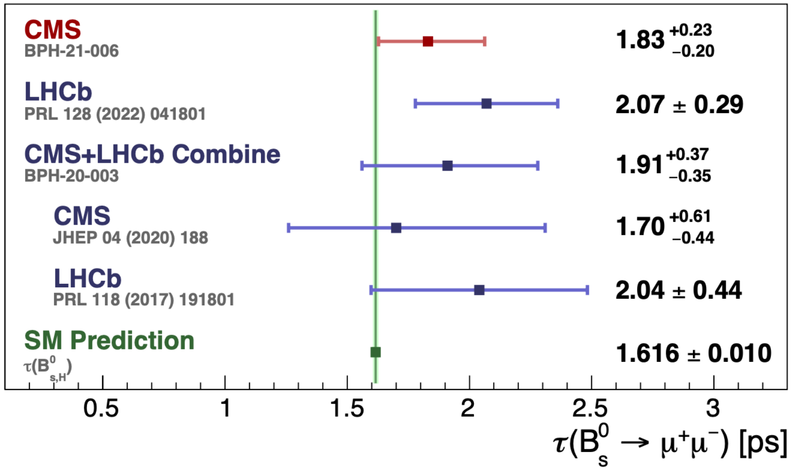
$$\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03\ \text{ps}$$

$$1.83\ ^{+0.23}_{-0.20}\ ^{+0.04}_{-0.04}\ \text{ps}$$

[CMS-PAS-BPH-21-006]

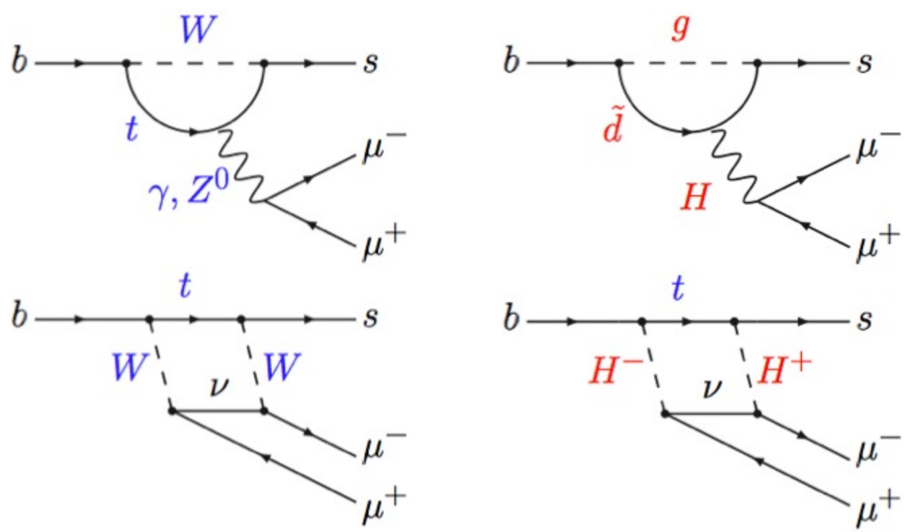


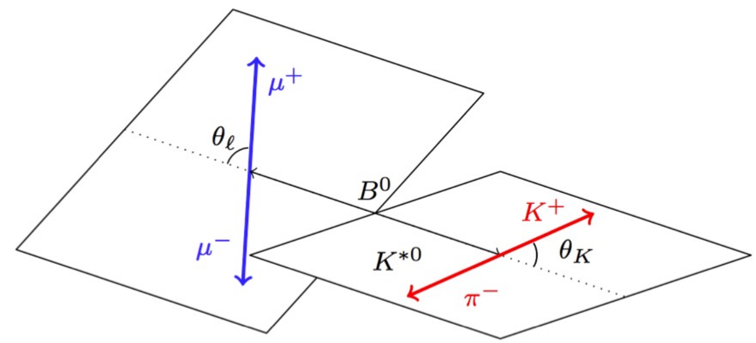
[De Bruyn *et al.*, PRL 109 (2012) 041801]



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

- Rates and angular distributions sensitive to NP

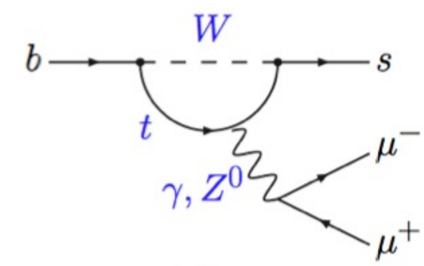


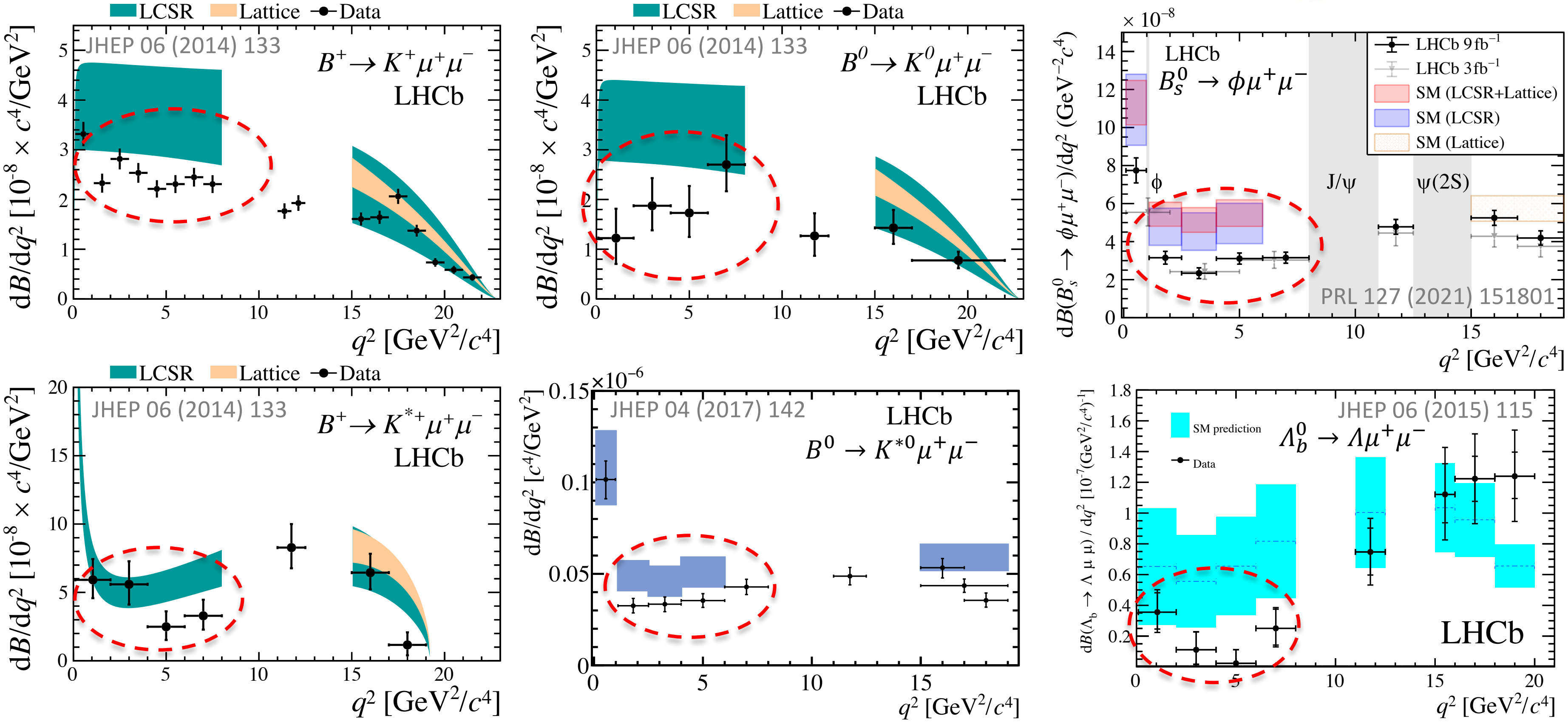


$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos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

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

- Pattern of tensions seen, theoretical uncertainty?



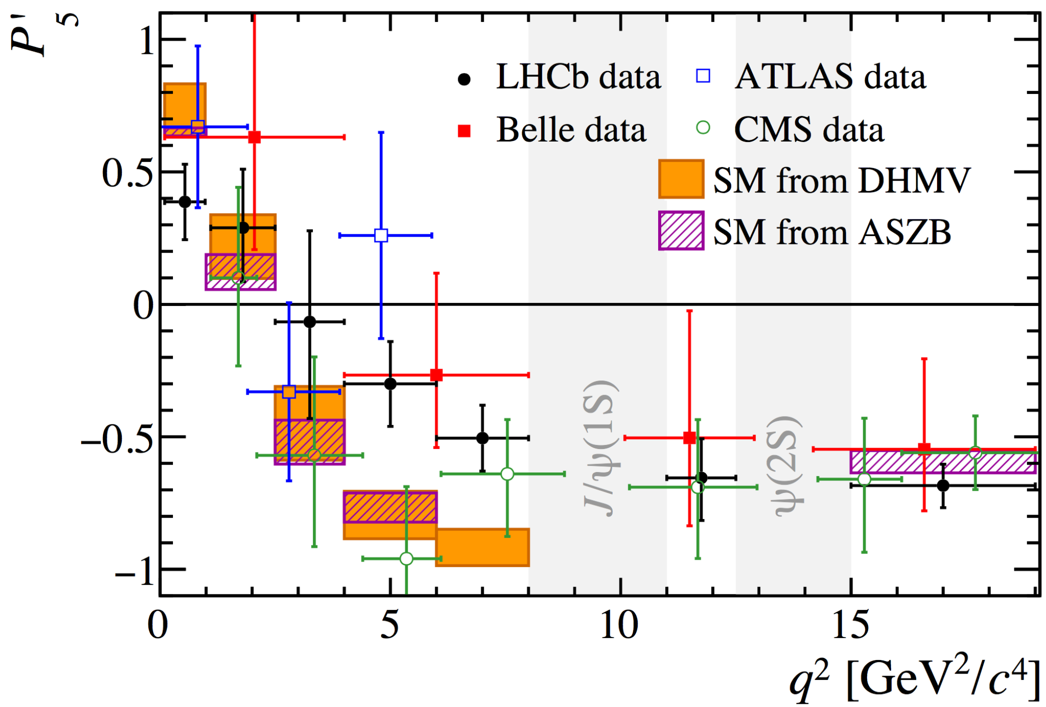


P_5' with $B^0 \to K^{*0}\mu^+\mu^-$

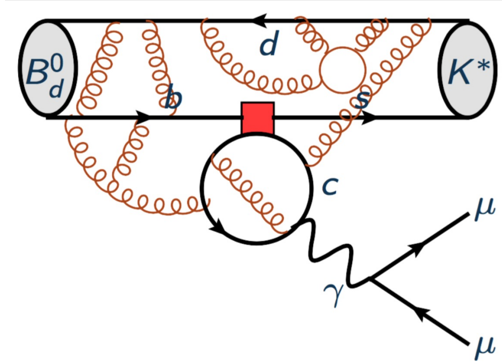
- $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$, less form-factor dependent

[S. Descotes-Genon, *et al.*, JHEP 01 (2013) 048]

- Also measured by Belle, ATLAS, CMS

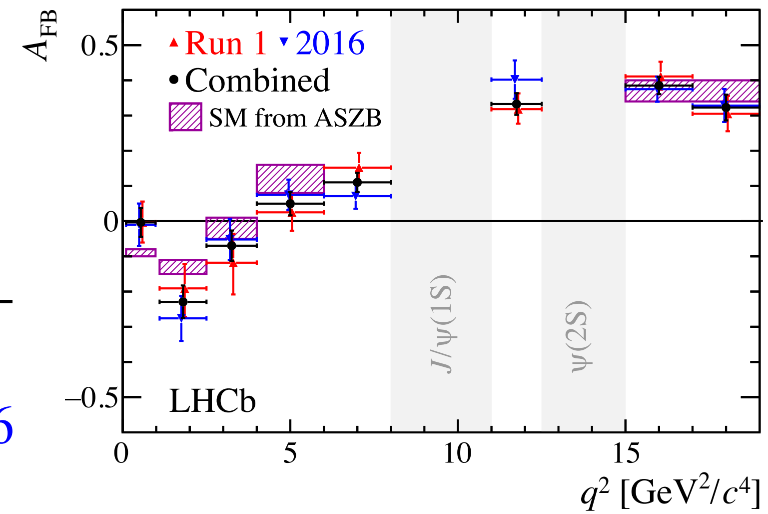


[LHCb, JHEP 02 (2016) 104]
[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

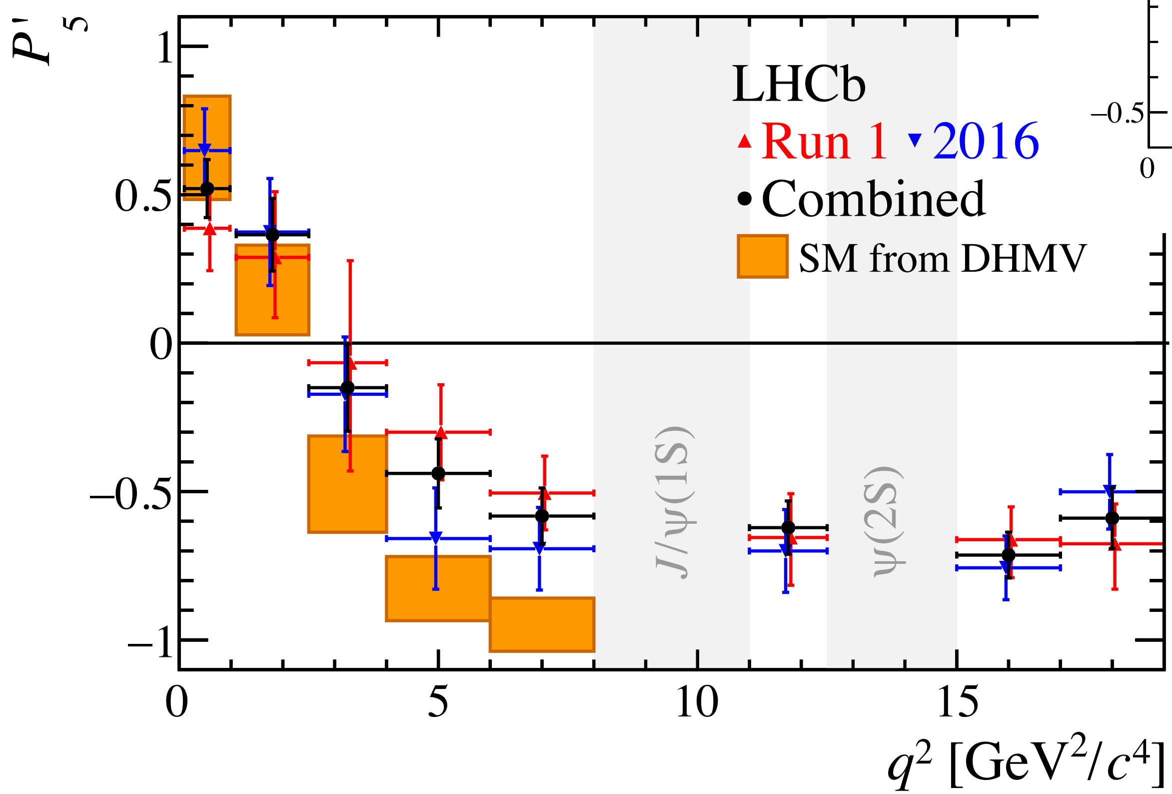


$B^0 \to K^{*0}\mu^+\mu^-$, latest results

- Updated with 2016 data

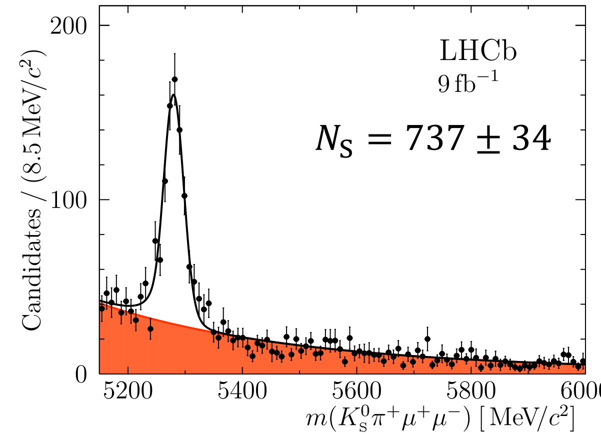


[PRL 125 (2020) 011802]

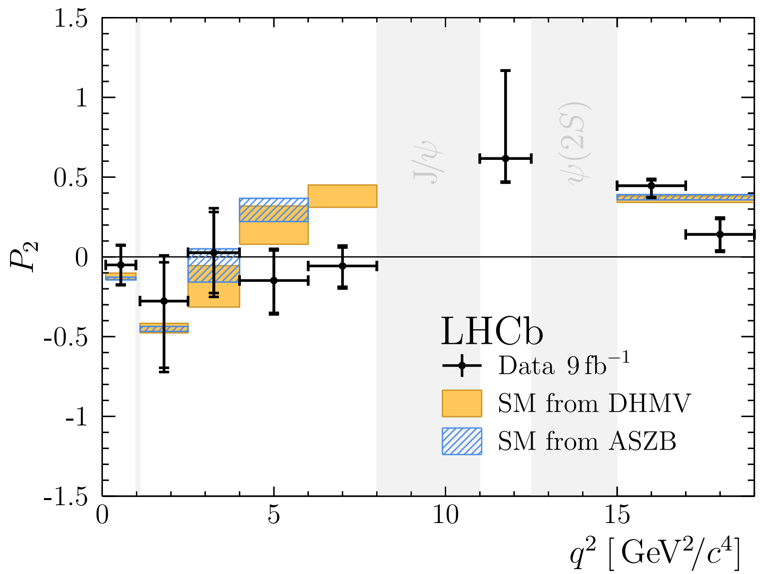


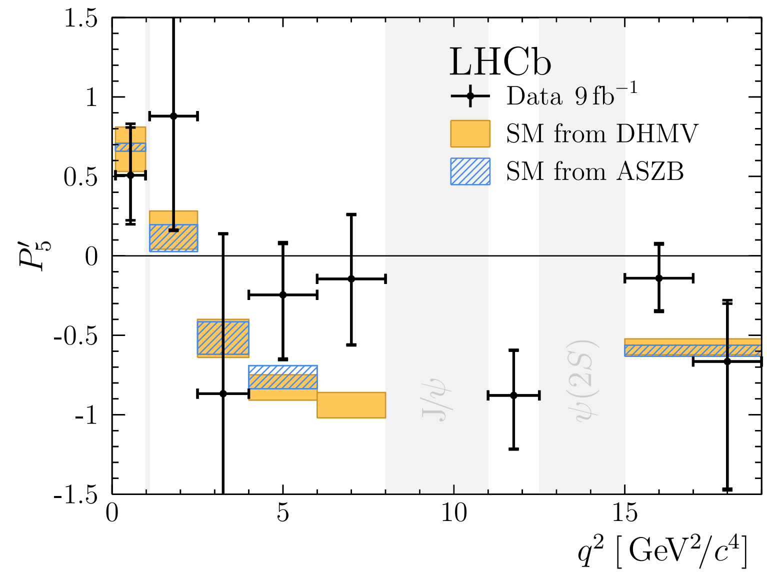
$P'_{5,2}$ with $B^+ \to K^{*+}\mu^+\mu^-$

- All data, $K^{*+} \to K^0_S \pi^+$
- Local deviation from SM, 3σ in $P'_2 = \frac{2}{3} A_{\mathrm{FB}} / (1 - F_L)$



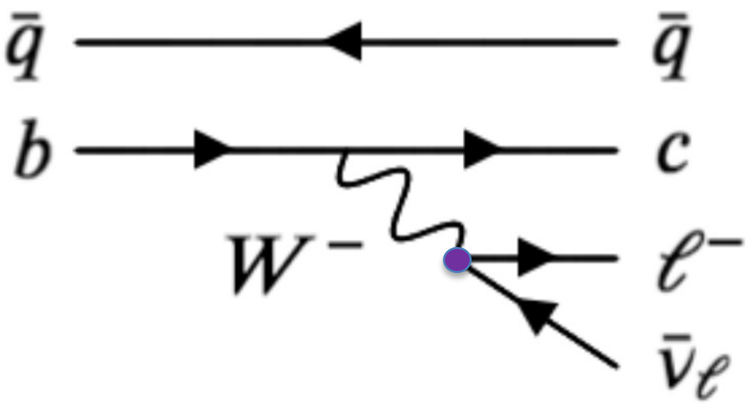
[PRL 126 (2021) 161802]

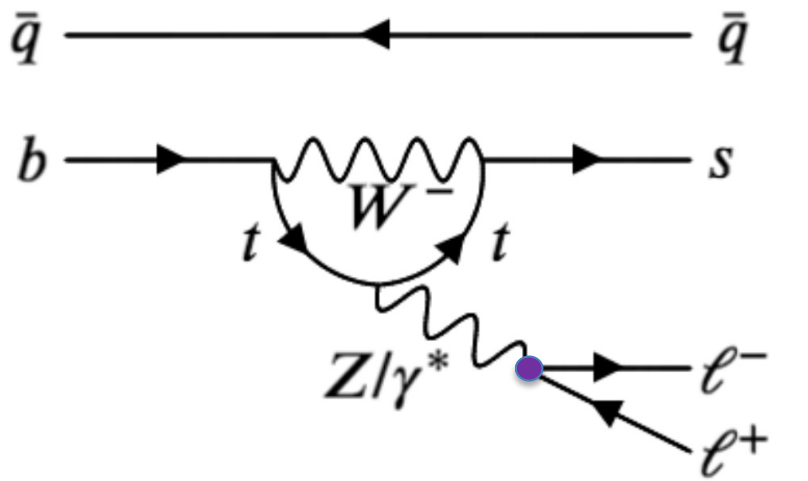




Lepton flavour universality

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





  – which means, e.g.,

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

$\mathcal{O}(10^{-4})$ uncertainty
[C. Bobeth *et al.*, JHEP 12 (2007) 040]

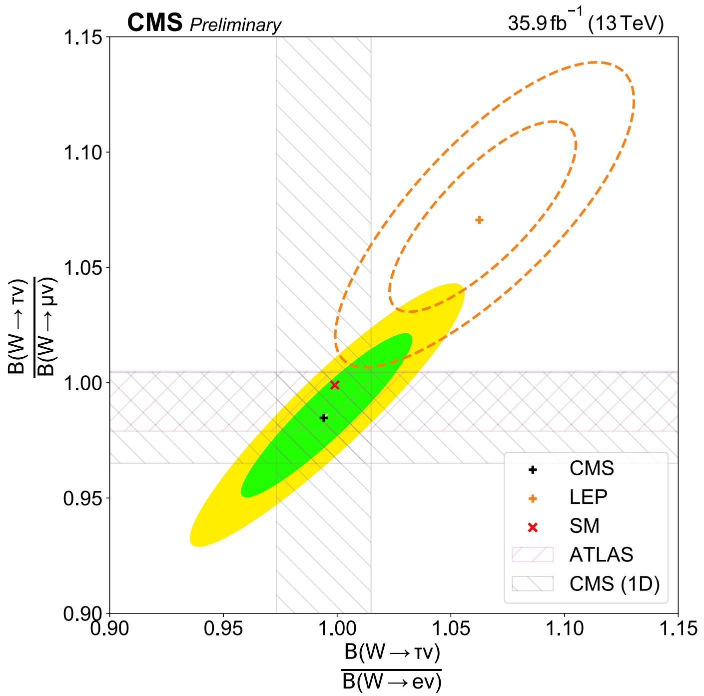
$\mathcal{O}(1\%)$ QED correction
[M. Bordone *et al.*, EJPC 76 (2016) 440]

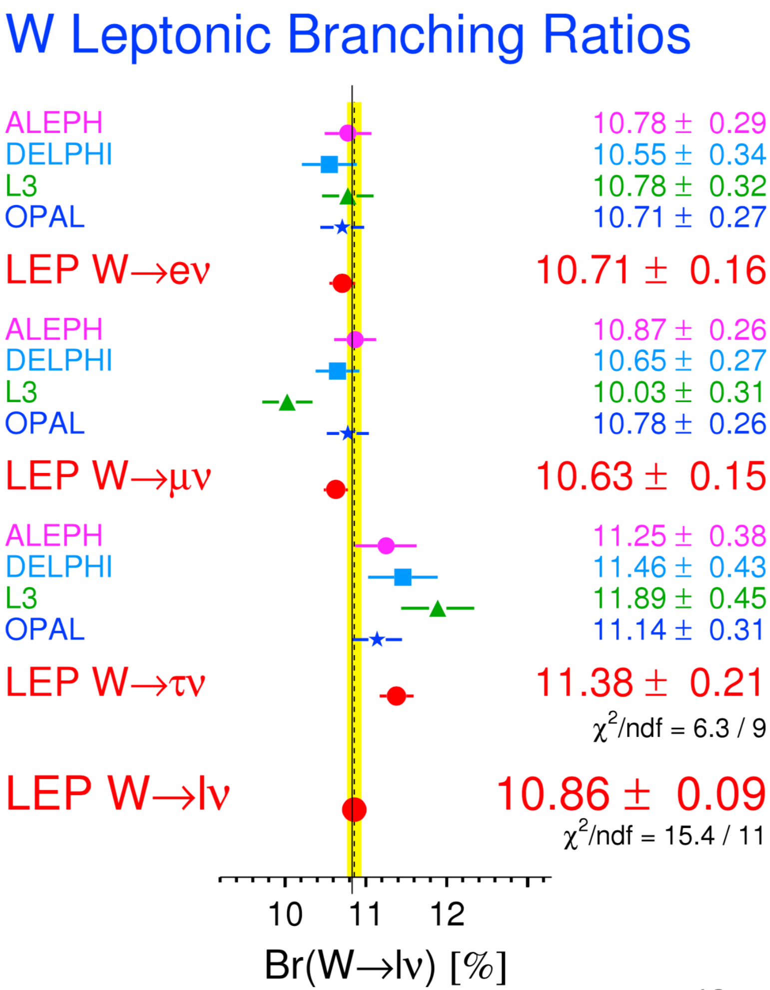
- Lepton flavor universality violation? New Physics!

Experimental test of LFU

- Well established in SM, e.g. $W \rightarrow \ell\nu$
  - Some tension at LEP, addressed by ATLAS/CMS

[arXiv:2007.14040, CMS PAS SMP-18-011]



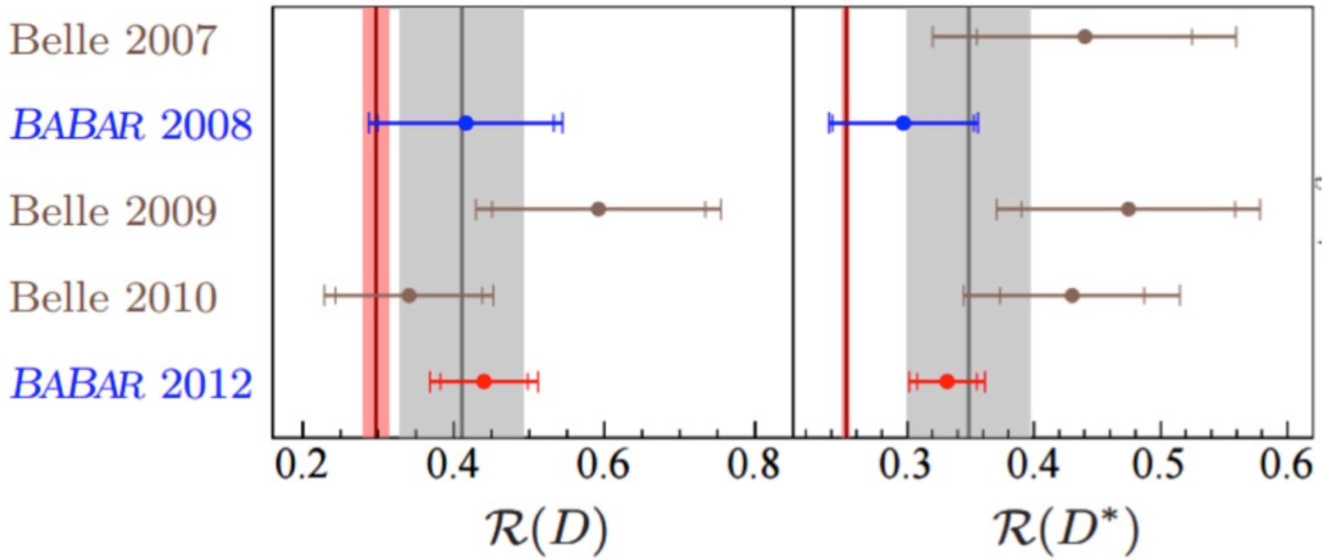


LFU in B system, pre-LHCb

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

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

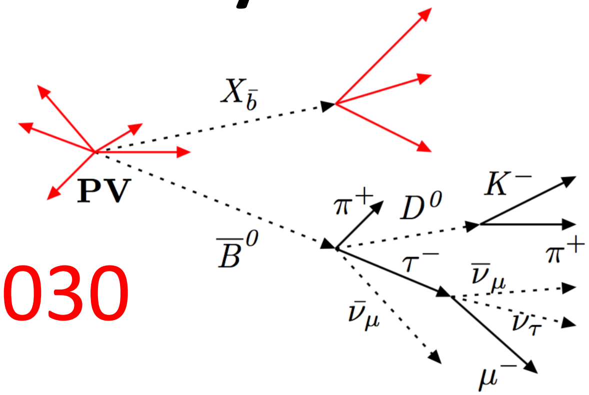
[Babar, PRD 88 (2013) 072012]

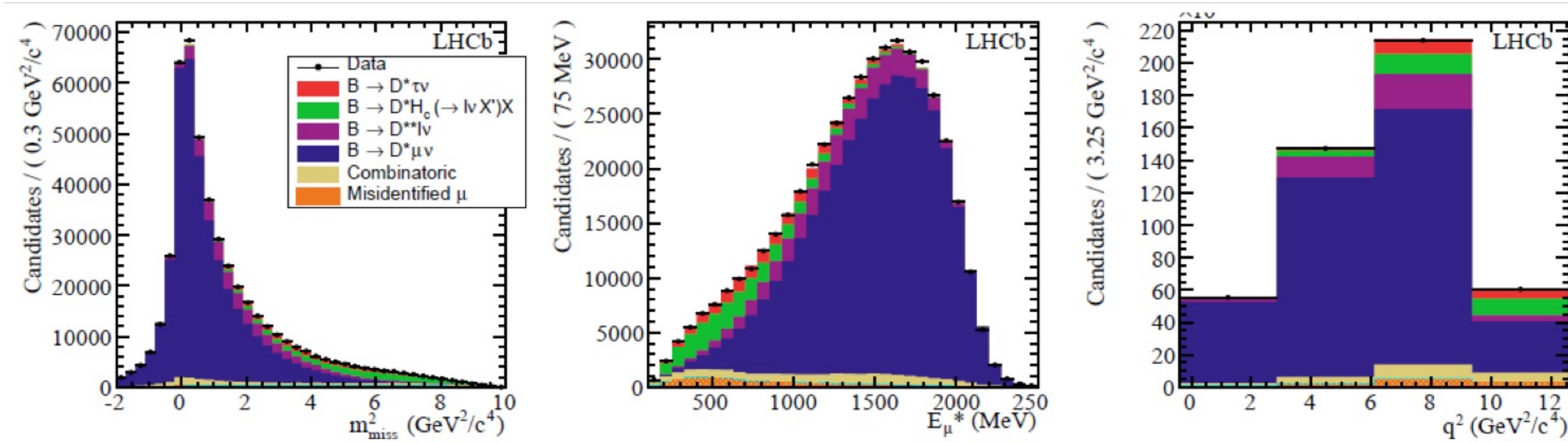


- No deviation seen in FCNC $b \to s\ell^+\ell^-$ decays

R(D*) using munoic τ decays

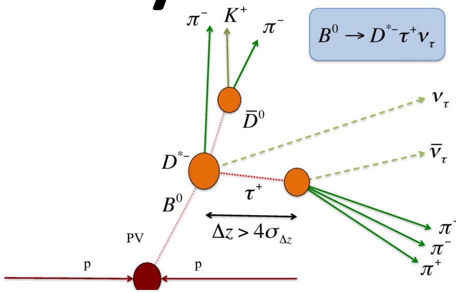
- $\mathcal{B}(\tau \to \mu X)$~17.4%
- 3D fits, R(D*)=0.336 ± 0.027 ± 0.030
  - Signal yields: 16 500 ± 1 670
  - Systematics: Simulation size, Mis-ID template, …





[PRL 115 (2015) 118003]

R(D*) using 3-prong τ decays

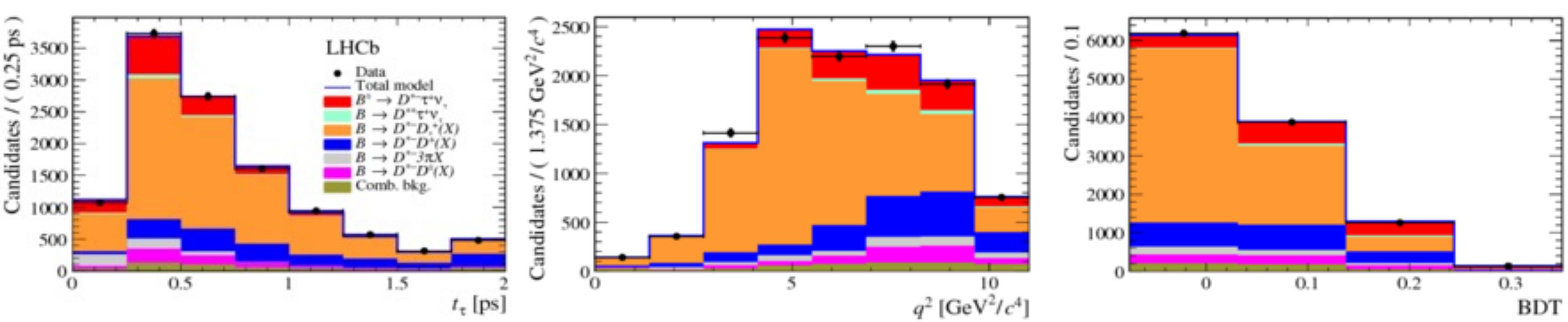


- $\mathcal{B}(\tau \to 3\pi^{\pm}X)$~9%+4%(≥1$\pi^0$)
- Normalized to $B^0 \to D^{*-}3\pi$

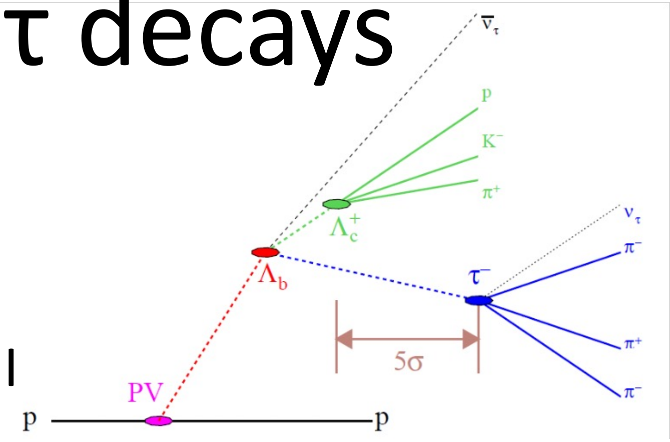
$$R_{had}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)} \quad R(D^*) = R_{had}(D^*) \times \frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^-\nu_\mu)}$$

- 3D fits, R(D*)=0.286 ± 0.019 ± 0.025 ± 0.021
  - Signal yields: 1273 ± 85
  - Systematics: Simulation size, $D \to 3\pi X$ template, ...

[PRL 120 (2018) 171802]



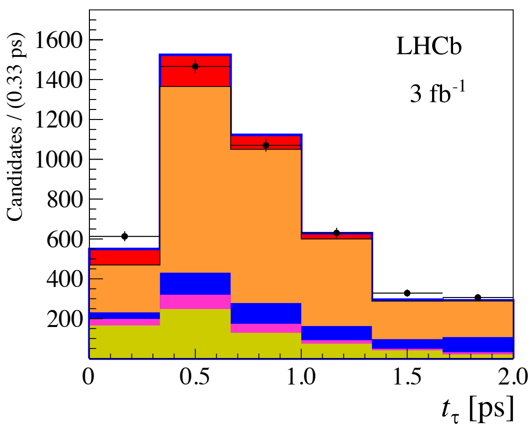
$R(\Lambda_c^+)$ using 3-prong τ decays

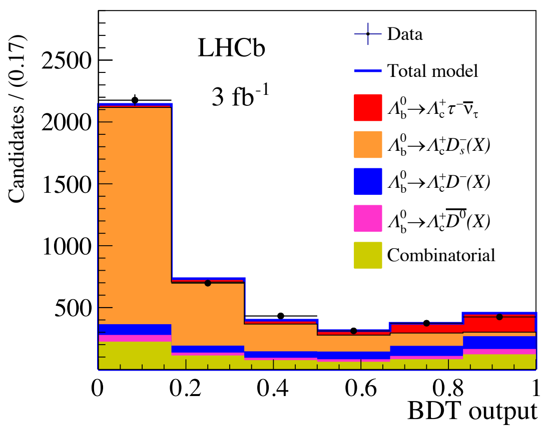


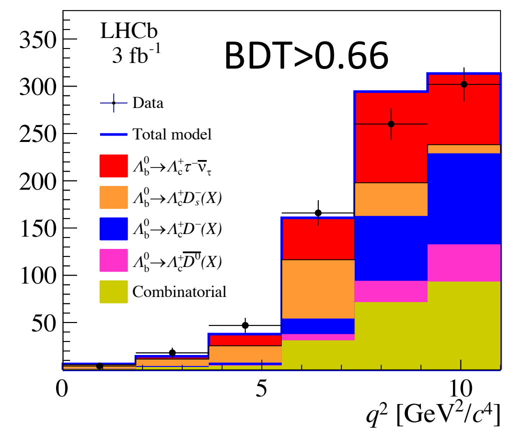
- Noramalized to $\Lambda_b^0 \to \Lambda_c^+ 3\pi$

  $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu) = (6.2 \pm 1.4)\%$ by DELPHI

- 3D fits, $R(\Lambda_c^+)$=0.242 ± 0.026 ± 0.040 ± 0.059
  - Signal yields: 349 ± 40
  - Systematics: $D \to 3\pi X$ template, $\Lambda_b^0 \to \Lambda_c^+ D X$

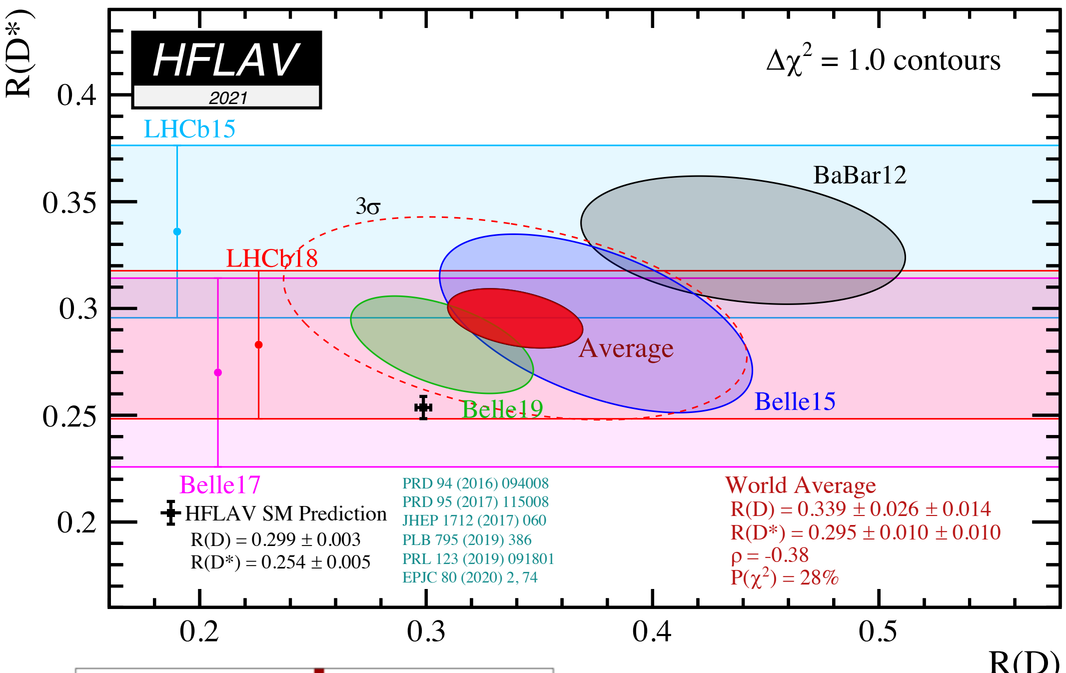


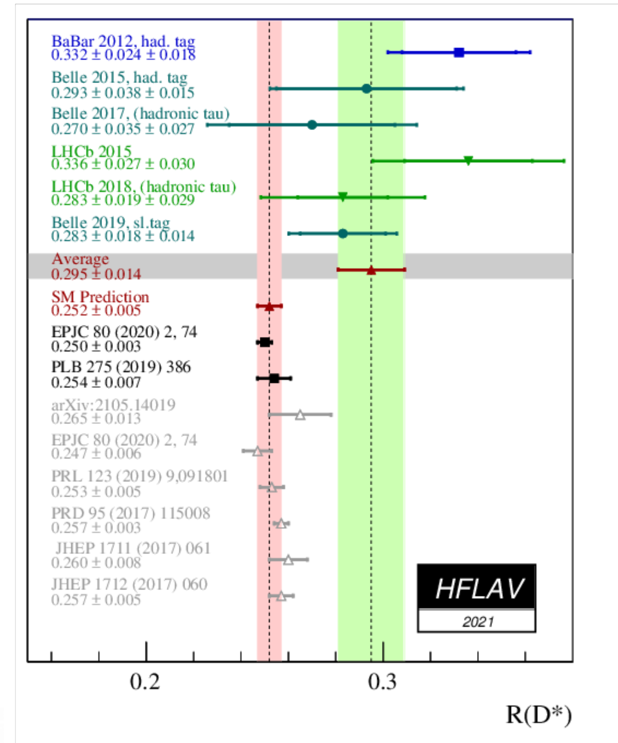


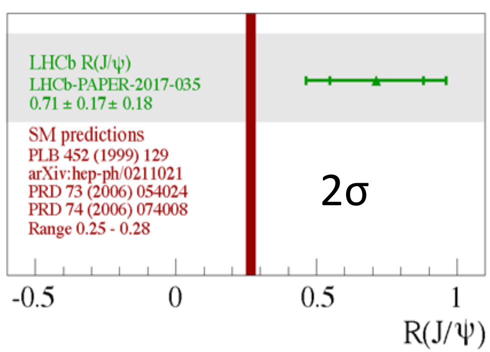


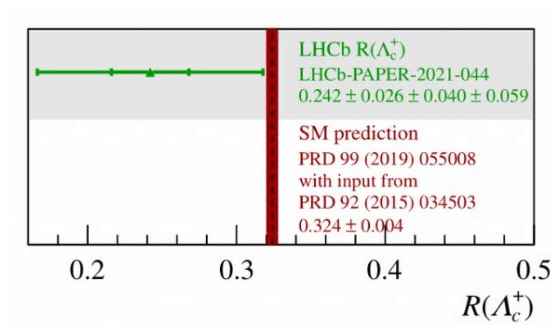
Summary of LFU in $b \to c\ell\nu$ decays

- Deviations from SM seen by Babar/Belle/LHCb



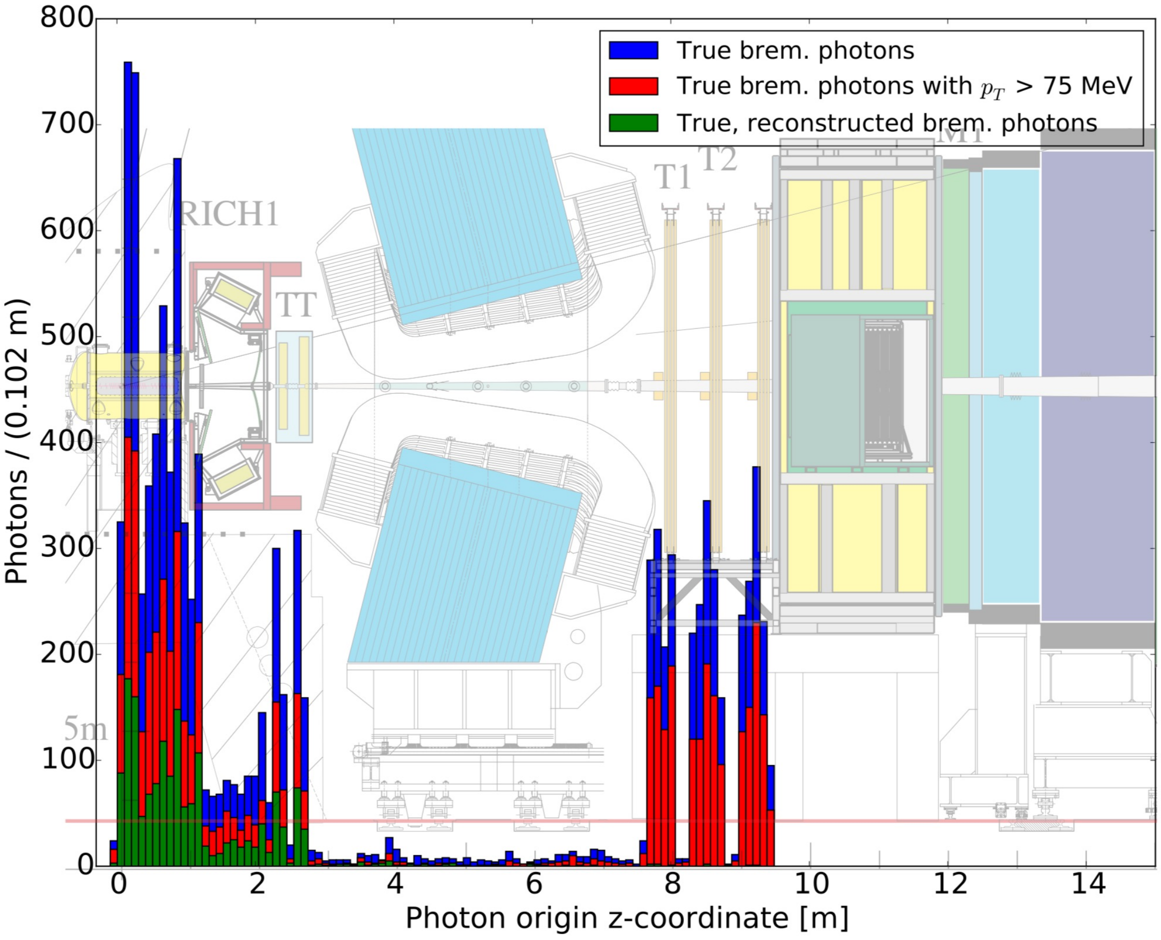


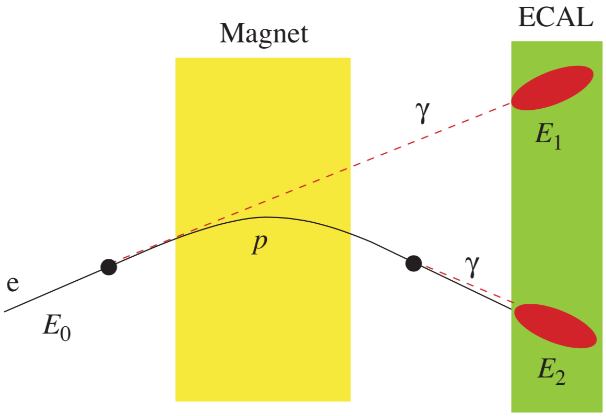


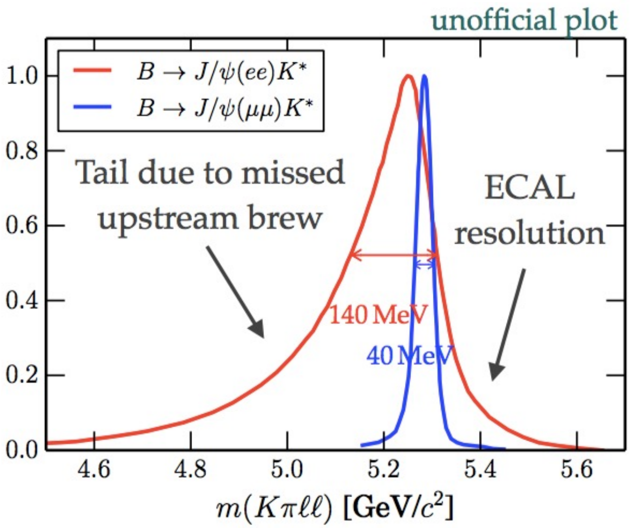


$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$$

Bremsstrahlung corrections







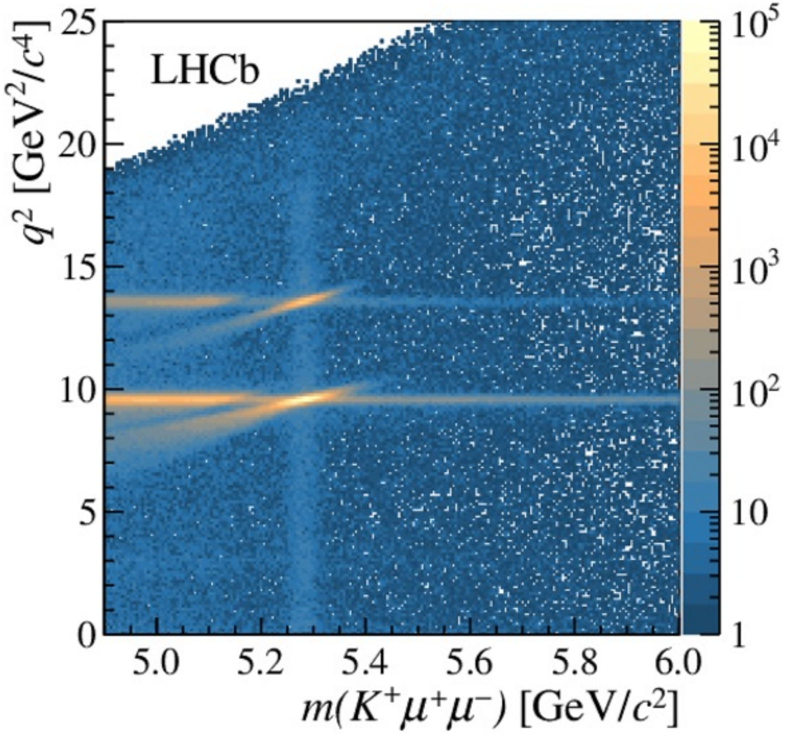
R(K), introduction

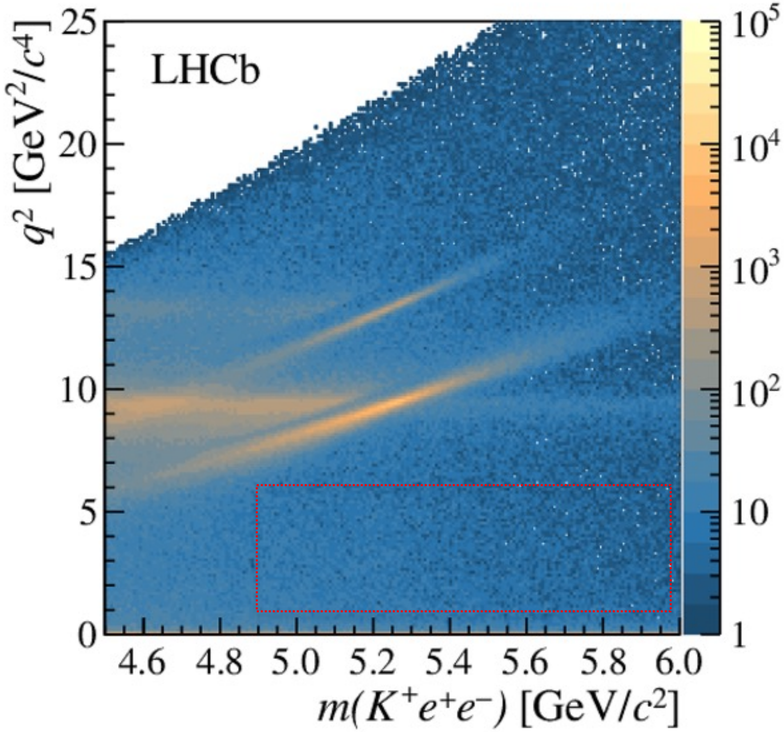
- Double ratio to control systematics

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

- Choice of $q^2 = m^2(\ell^+\ell^-)$

[PRL 122 (2019) 191801]

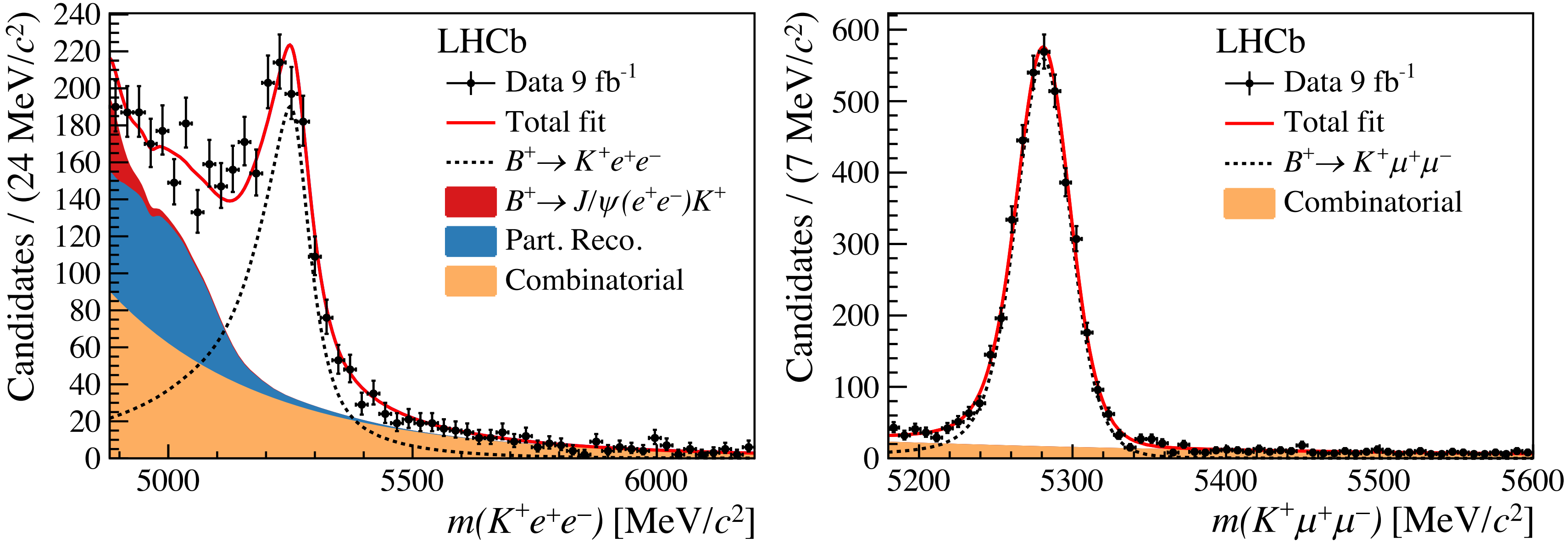




Signal yields with all data

- 9 fb^{-1} of data, $1.1 < q^2 < 6.0\ \text{GeV}^2/c^4$
  - $N(B^+ \to K^+ e^+ e^-) = 1640 \pm 70$
  - $N(B^+ \to K^+ \mu^+ \mu^-) = 3850 \pm 70$

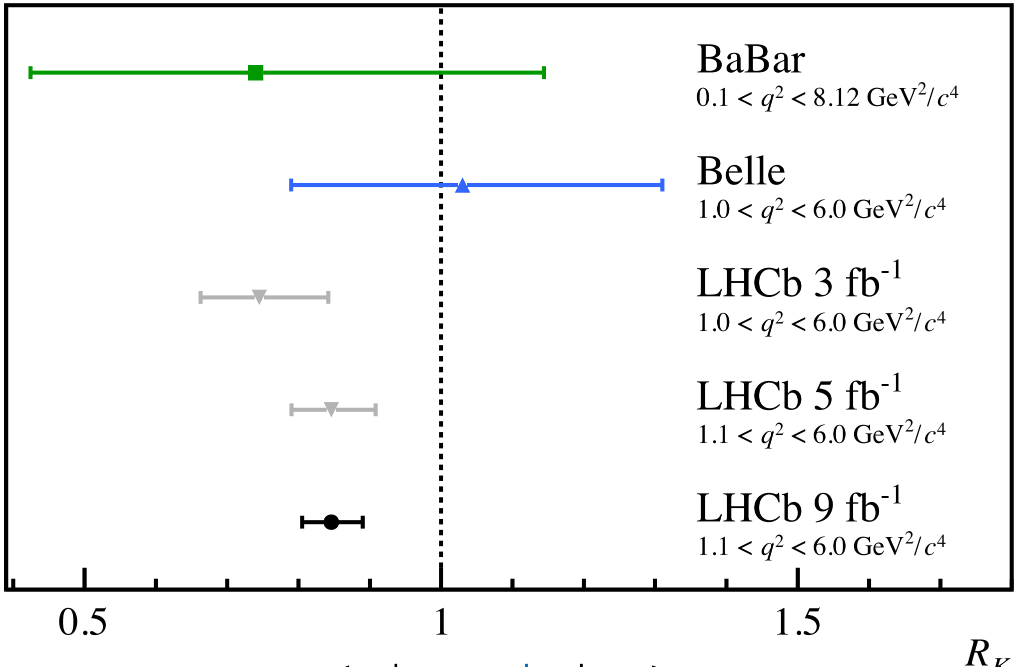
[NP 18 (2022) 277]

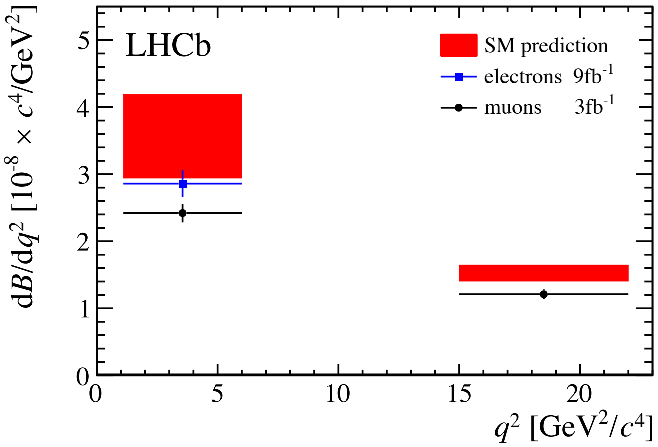


R(K), latest results

- Deviation from SM, 3.1σ by LHCb
- Electron mode more close to SM prediction?

[NP 18 (2022) 277]

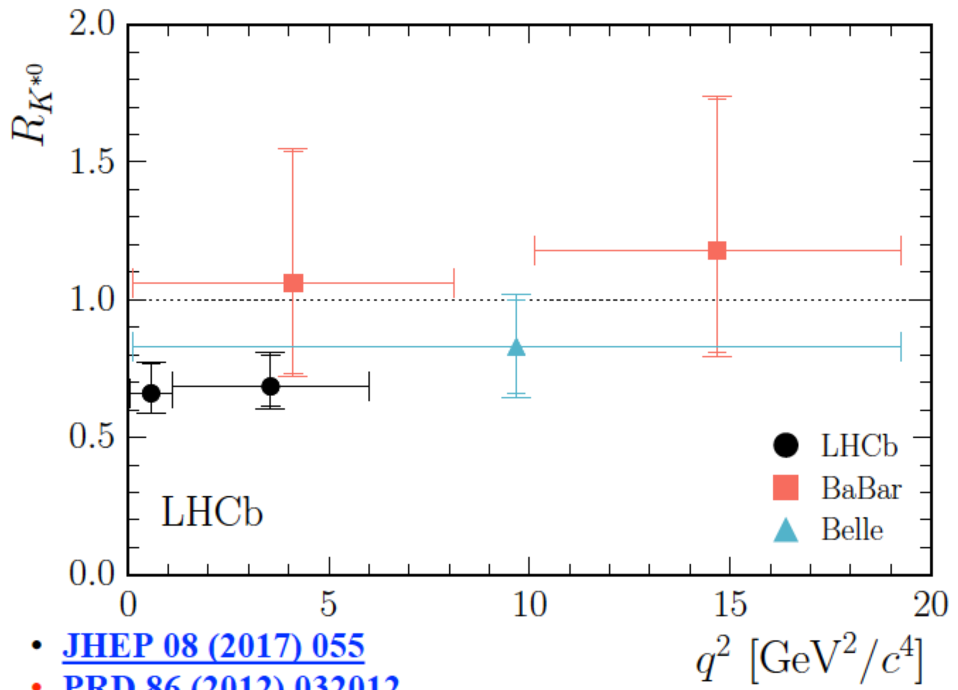


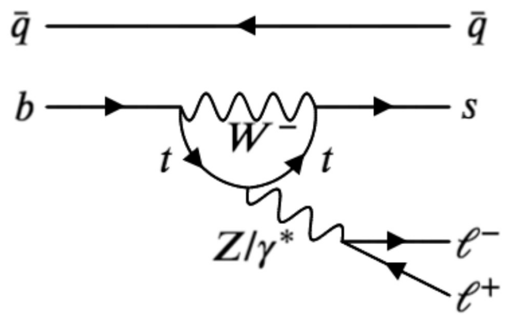


$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 0.846\ ^{+0.042}_{-0.039}\ ^{+0.013}_{-0.012}$$

R(K*0), results with Run-I data

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





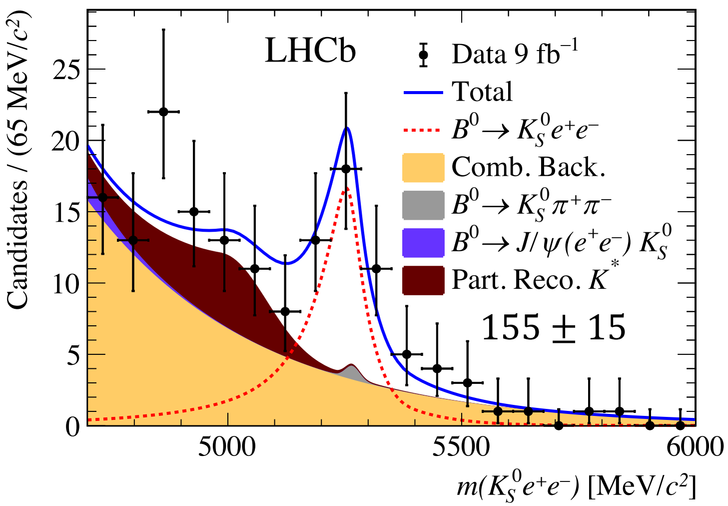
- JHEP 08 (2017) 055
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

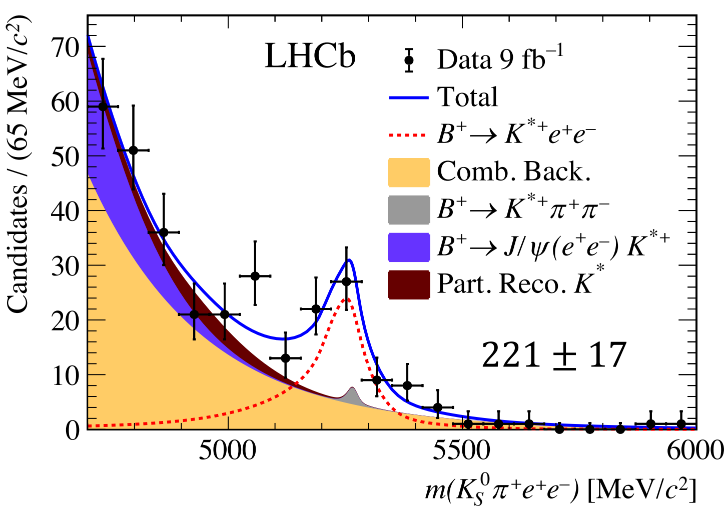
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

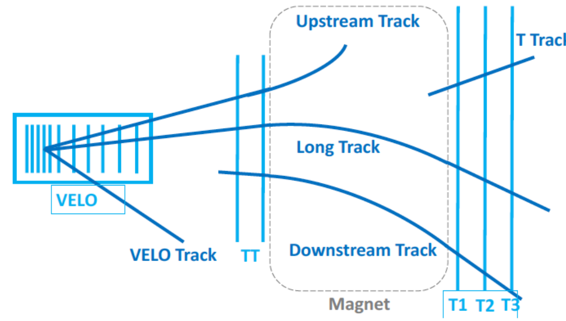
R(K_S^0) & R(K^{*+})

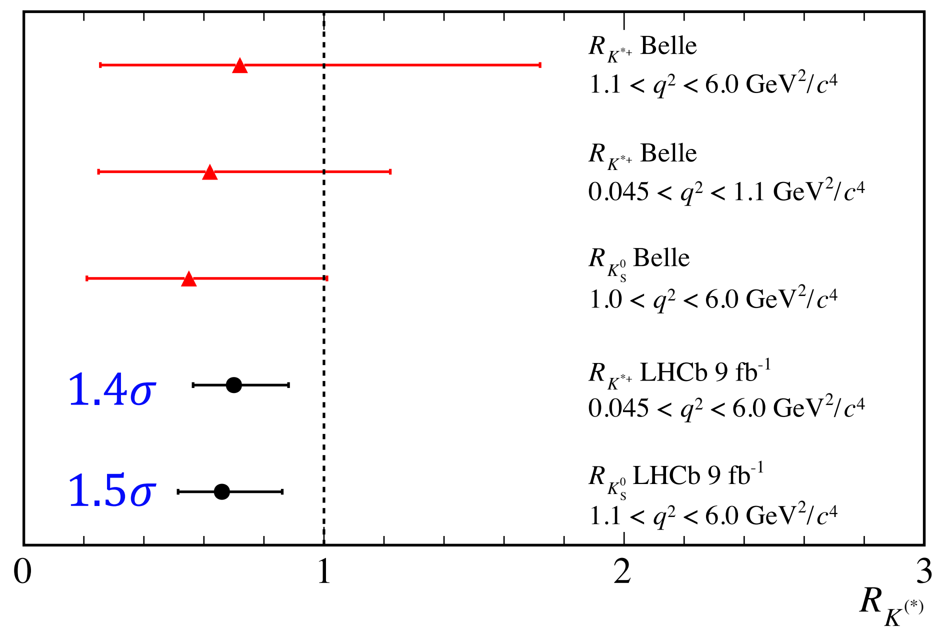
- Tests of LFU using K_S^0

[arXiv:2110.9501]





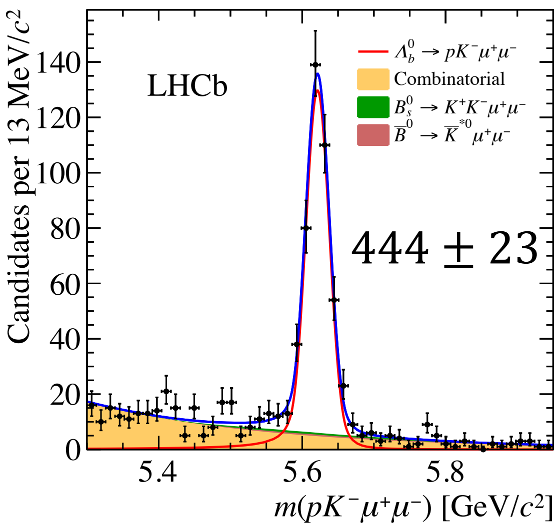


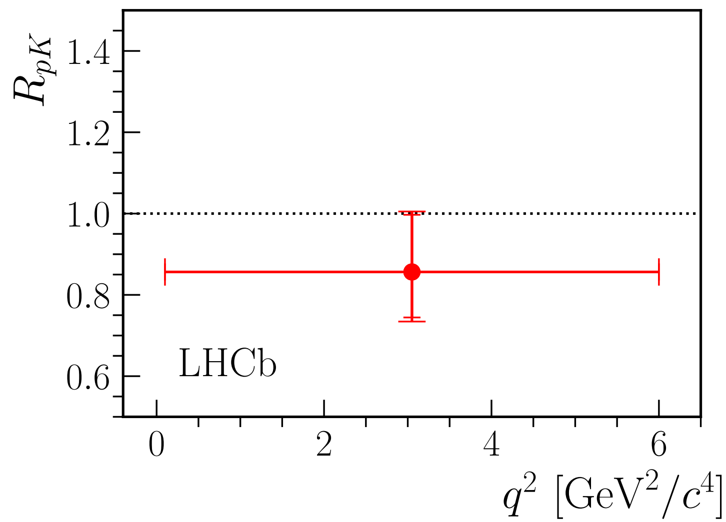


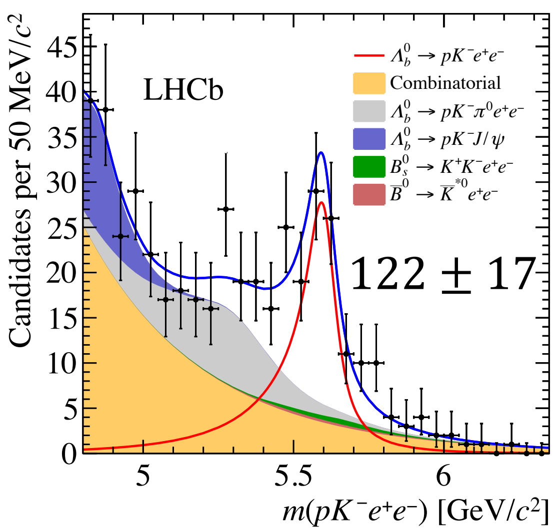
LHCb combined significance w.r.t. SM: 2σ

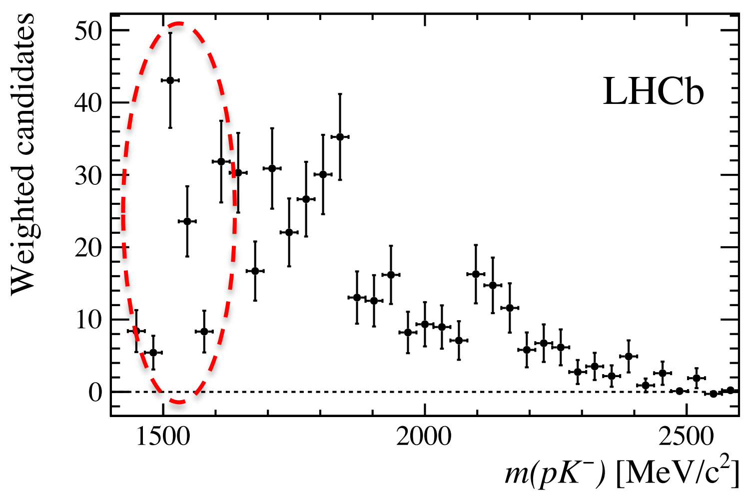
R(pK), results with Run-I+2016

- Compatible with 1, difficult to predict R(pK)?







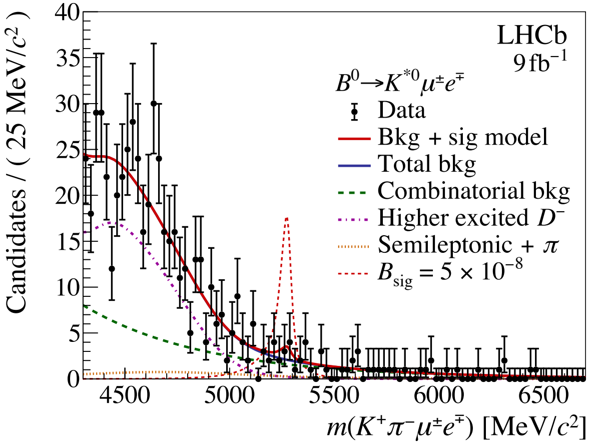


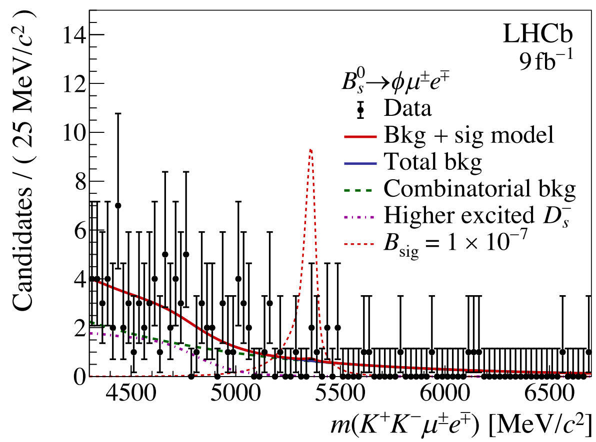
[JHEP 05 (2020) 040]

Search for LFV decays

[arXiv:2207.04005, LHCb-Paper-2022-021]

- $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\pm}$





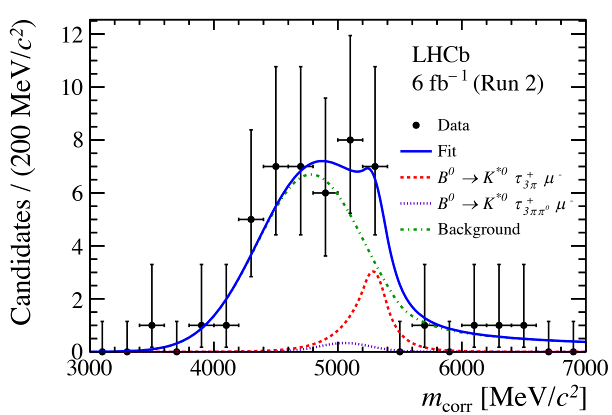
$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 10.1 \times 10^{-9}$$
$$\mathcal{B}(B_s^0 \to \phi\mu^{\pm}e^{\mp}) < 16.0 \times 10^{-9}$$

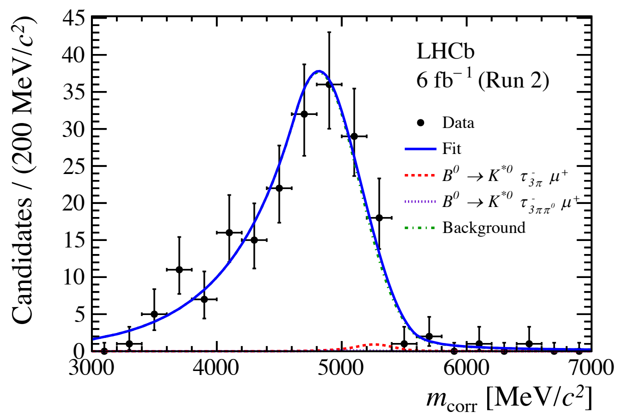
@ 90% CL

- $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

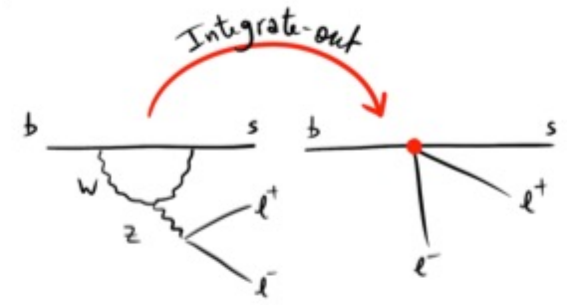
$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0\ (1.2) \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2\ (9.8) \times 10^{-6}$$

@ 90% (95%) CL





Effective Field Theory of $b \to sll$



- Integrate out short-distance (high energy) interactions

- Operator production expansion

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + h.c.$$

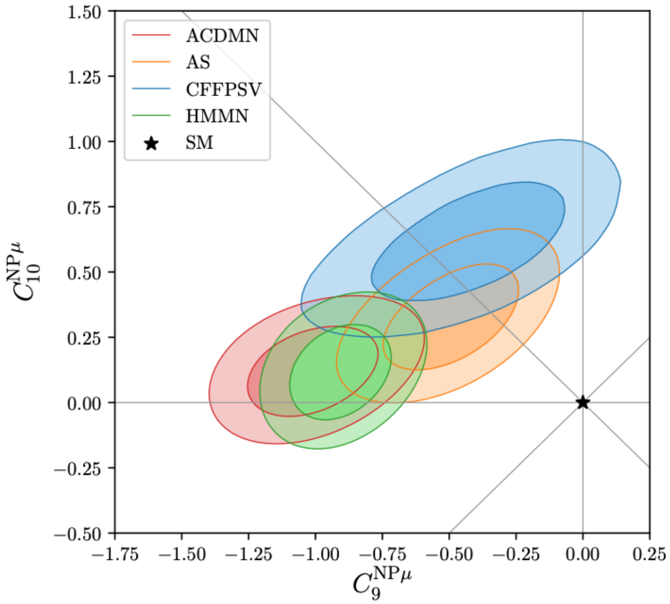
  – Wilson coefficients $C_i^{(\prime)}$ encode short-distance physics

  – Operators $O_i^{(\prime)}$ describe low-enery QCD (using form factors), which have large theory uncertainties

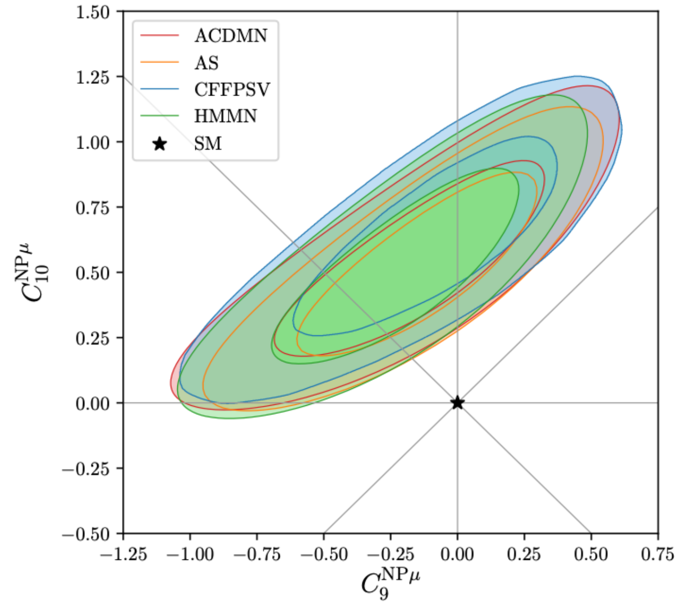
Global fit

- Different experimental inputs, form factors, assumptions about non-local matrix elements , statistical frameworks

B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl @ LHCb implications 2021 [slides]



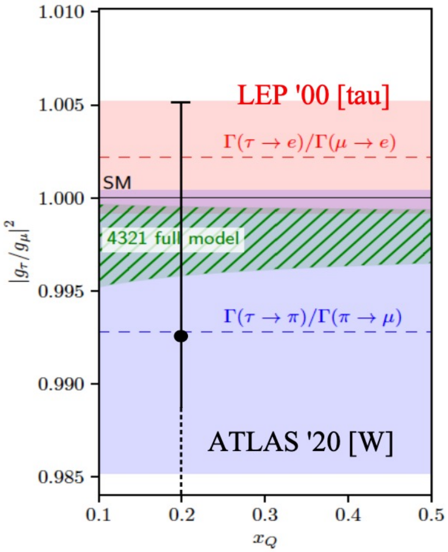
global fit



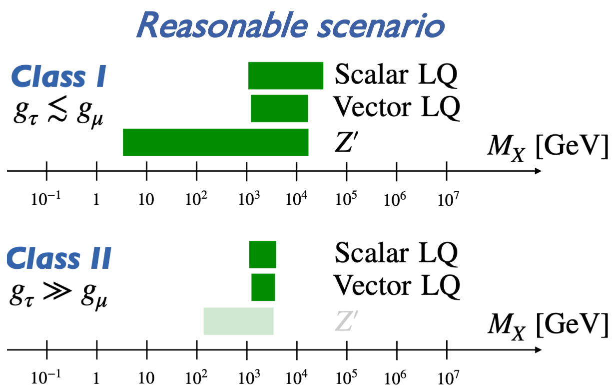
fit to LFU observables + $B_s \to \mu\mu$

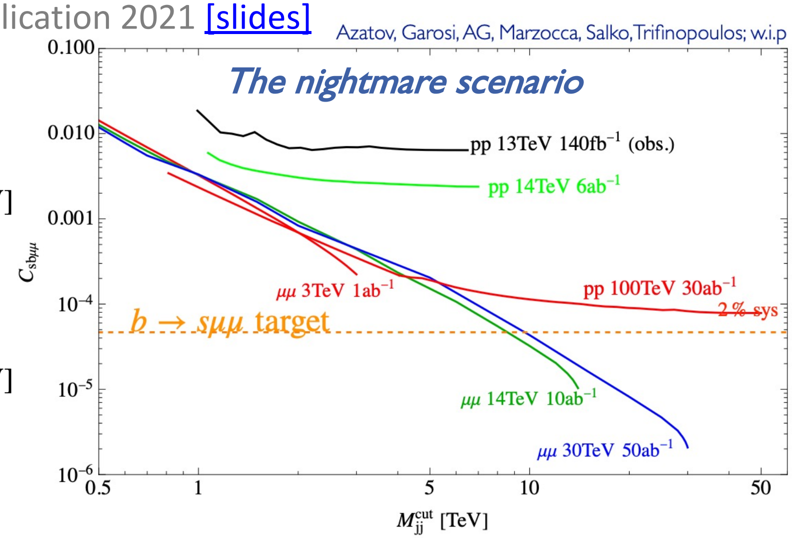
Implications?

G. Isidori @ NJNU

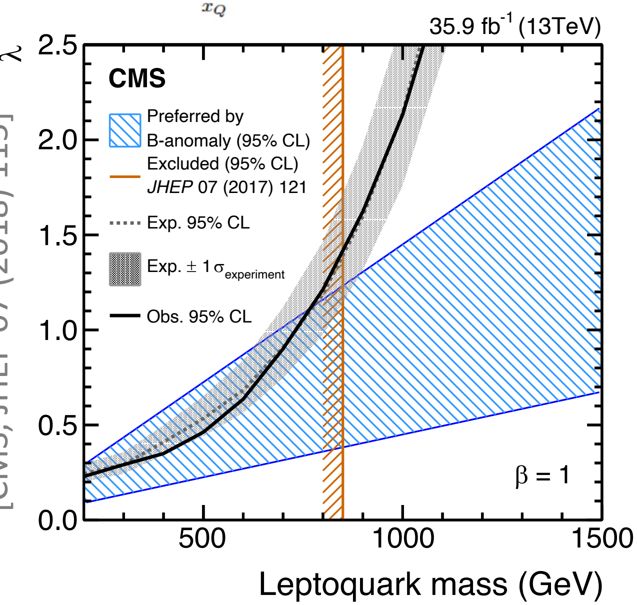


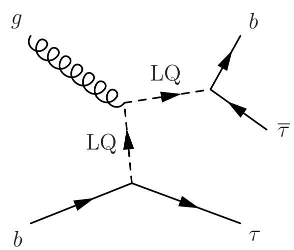
A. Greljo @ LHCb implication 2021 [slides]

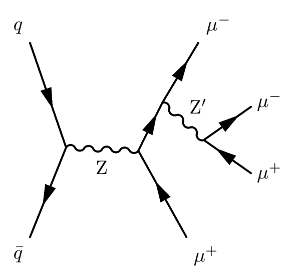


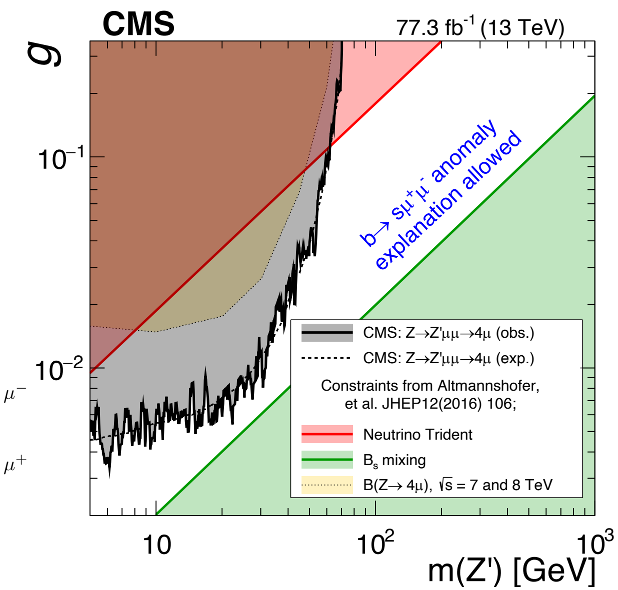


[CMS, JHEP 07 (2018) 115]









[CMS, PLB 792 (2019) 345]

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
$R_K(1 < q^2 < 6\text{ GeV})$	0.05	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%
$\tau_{B_s^0 \to \mu^+\mu^-}$	14%	8%		2%	4%?
$R(D^*)$	0.026	0.0072	0.005	0.002	
$R(J/\psi)$	0.24	0.071		0.02	

Summary

- Some anomalies seen at LHCb
  - Electroweak penguin, differential branching fraction, P_5' in $B \to K^* \mu^+ \mu^-$, $\mathcal{R}_{K^{(*0)}}$
  - LFU in semi-leptonic decay, $\mathcal{R}_{D^*}$

  to be confirmed or refuted with more data
- Your suggestions are always appreciated!