Flavour anomalies at LHCb

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Large Hadron Collider

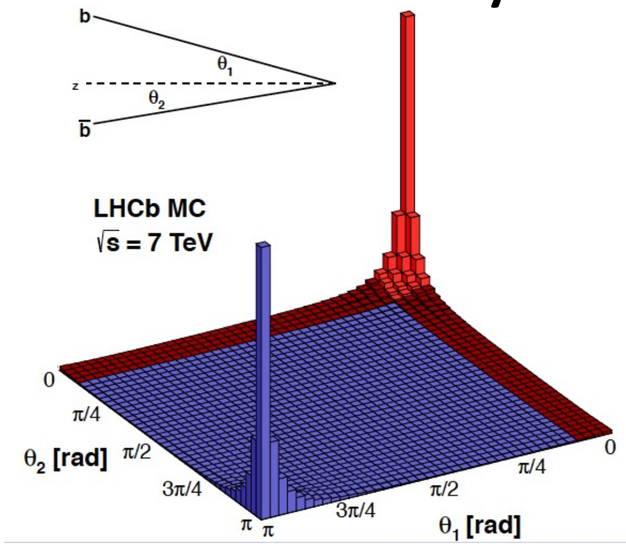
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

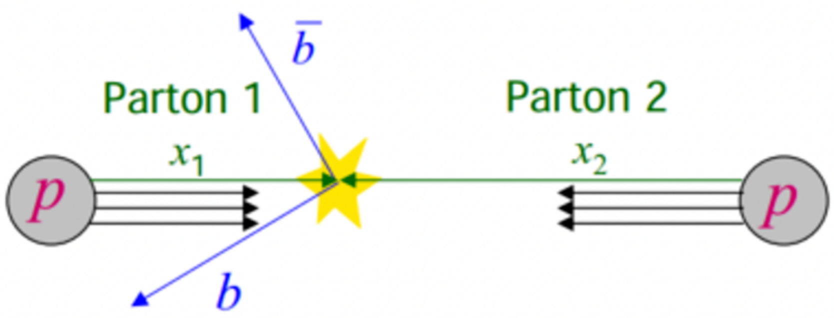
Beauty/charm production

- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb
  - Beauty ~0.3 mb **c.f. 1nb @$\Upsilon(4S)$**

} Flavor factory!

- Predominantly in forward/backward cones

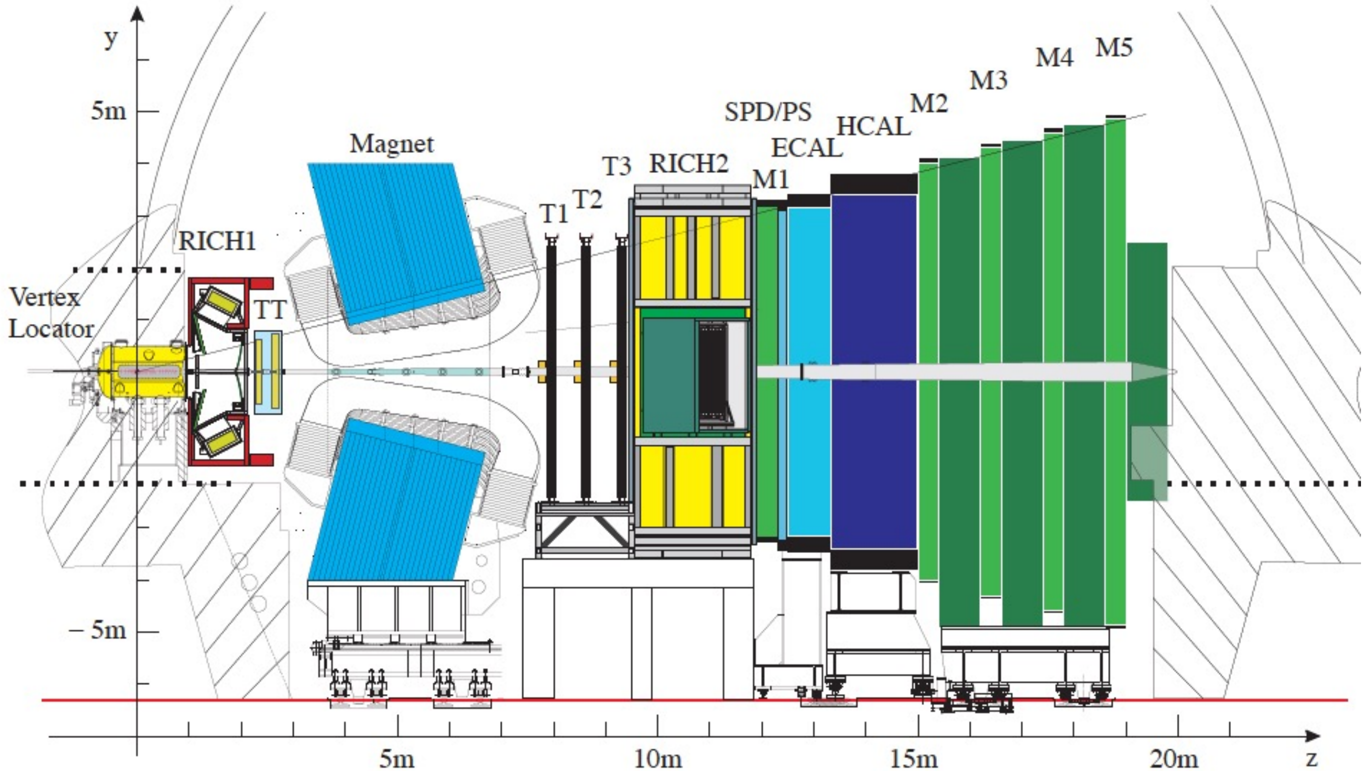




Beauty/charm signature

- Compared to minimum bias (background)
  - Relatively high mass → high *transverse momentum*
  - Relatively long lifetime → large impact parameter (IP)
- Requires excellent vertexing, tracking, particle-identification

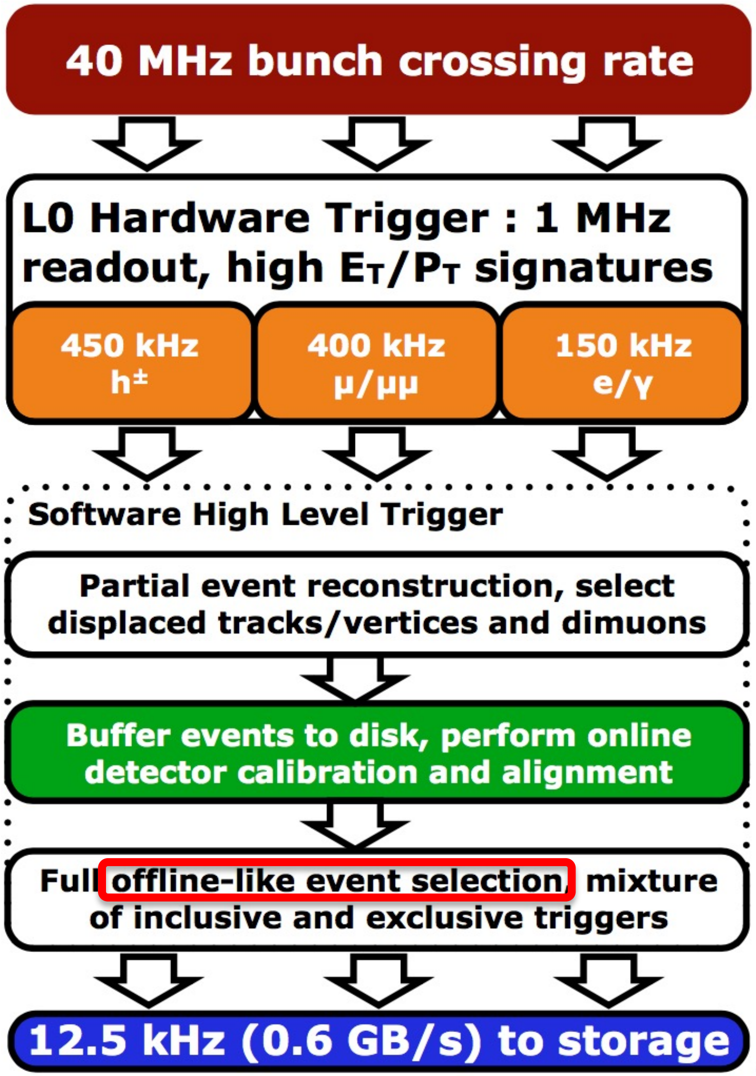
The LHCb experiment



[JINST 3 (2008) S08005]

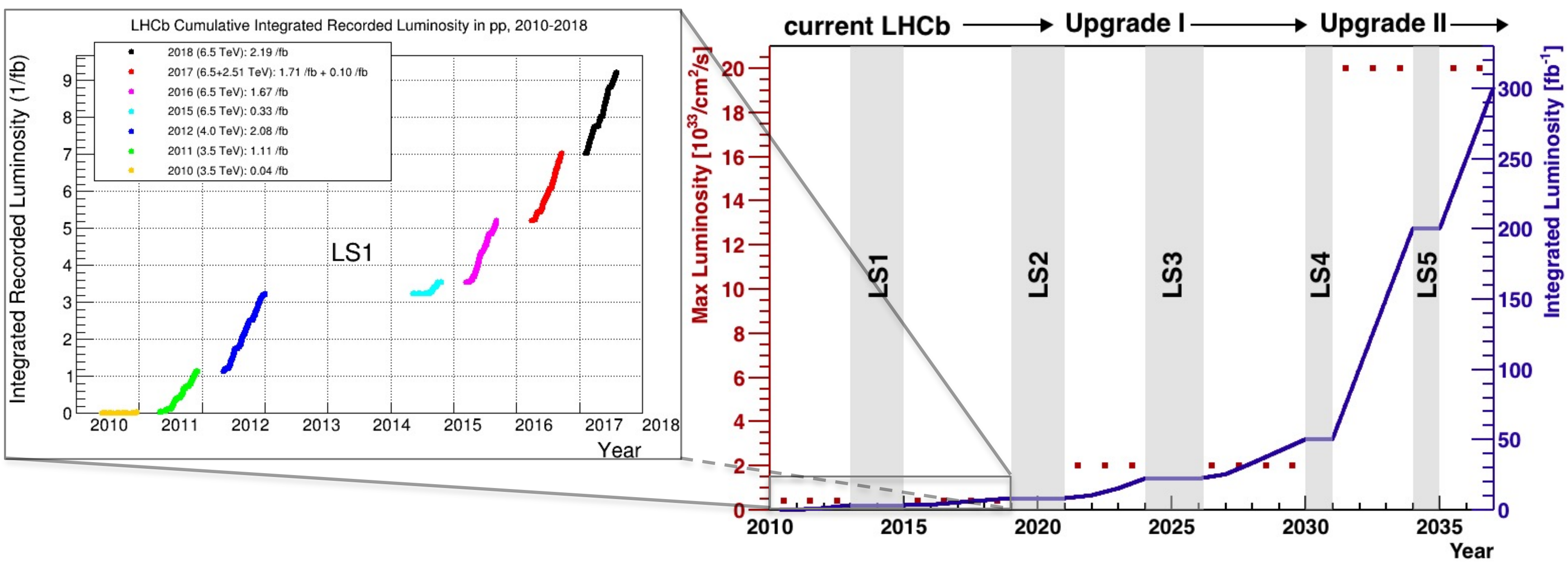
Vertex Locator	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to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

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, partial Rec
  - Stage1, 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} ??

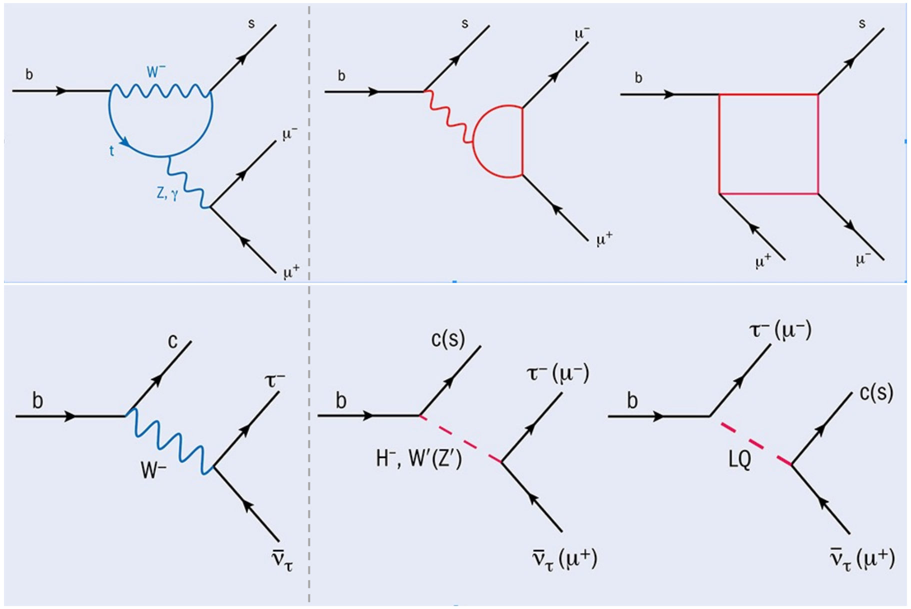
Phase-1 Upgrade!!

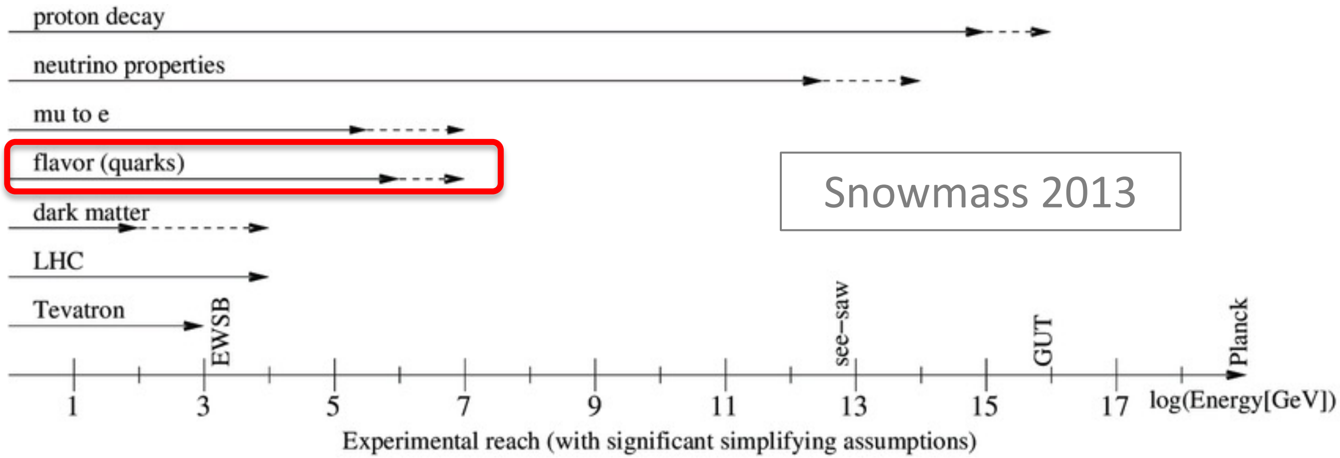
Phase-1b Upgrade!?

Phase-2 Upgrade??

Indirect search for New Physics

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

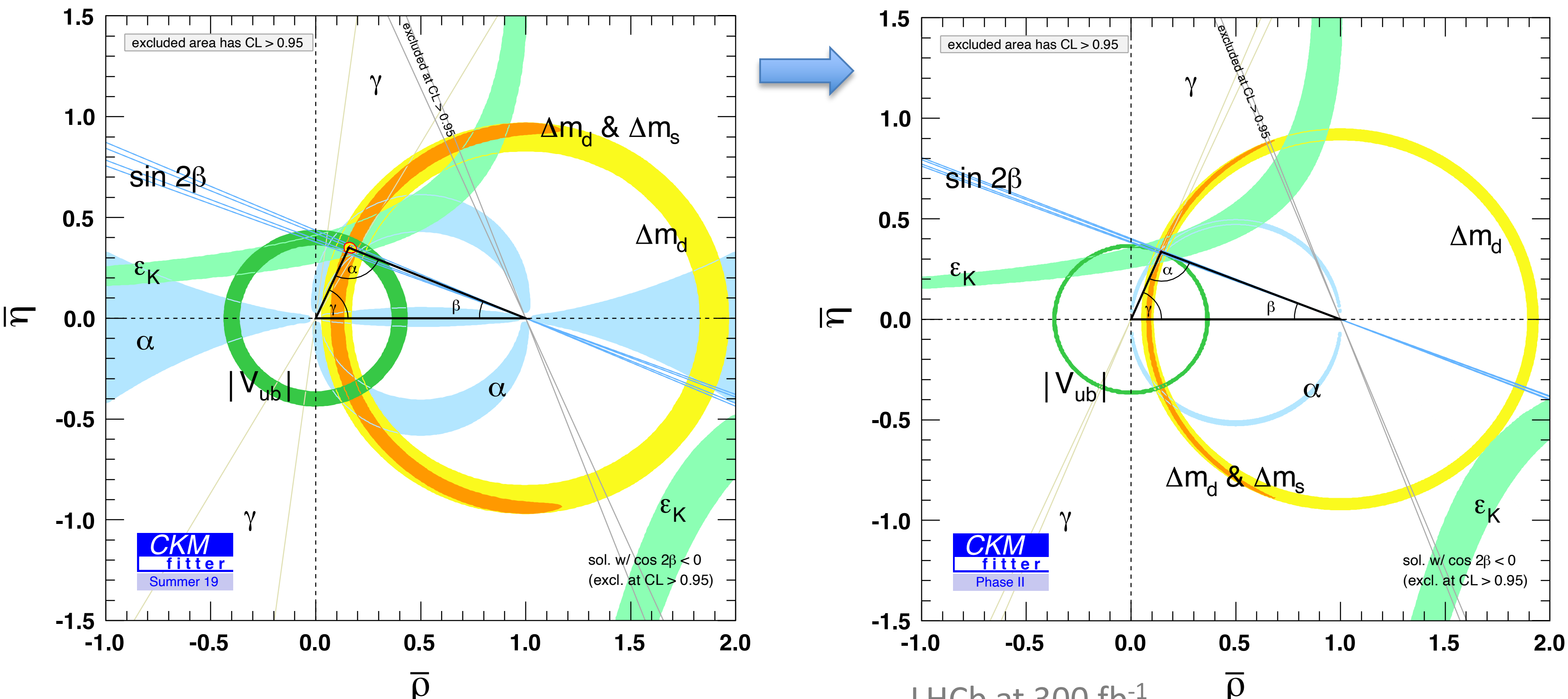




Snowmass 2013

Another way of search for NP

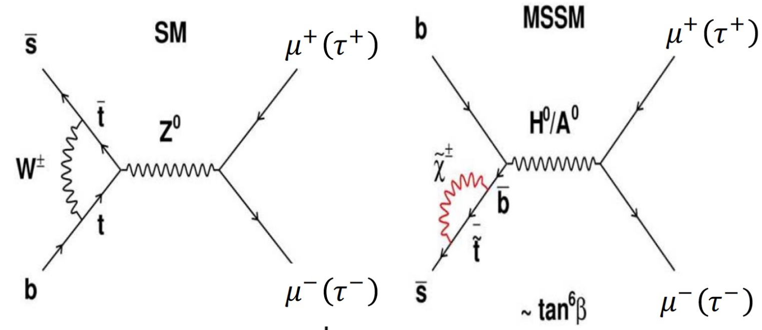
- Overconstrain the CKM triangle

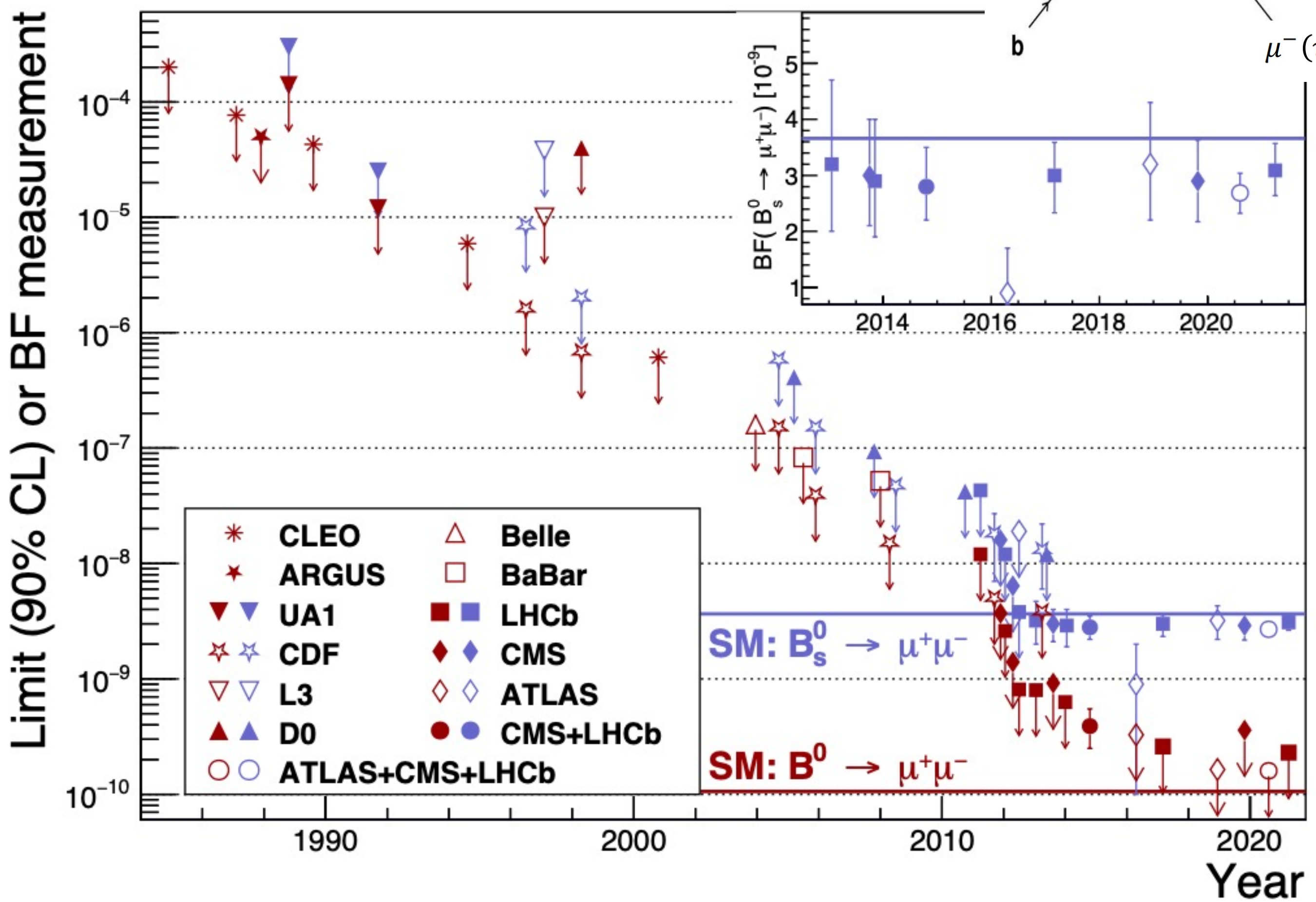


LHCb at 300 fb^{-1},
CMS/ATLAS at 3000 fb^{-1}, Belle II at 50 ab^{-1}.

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

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

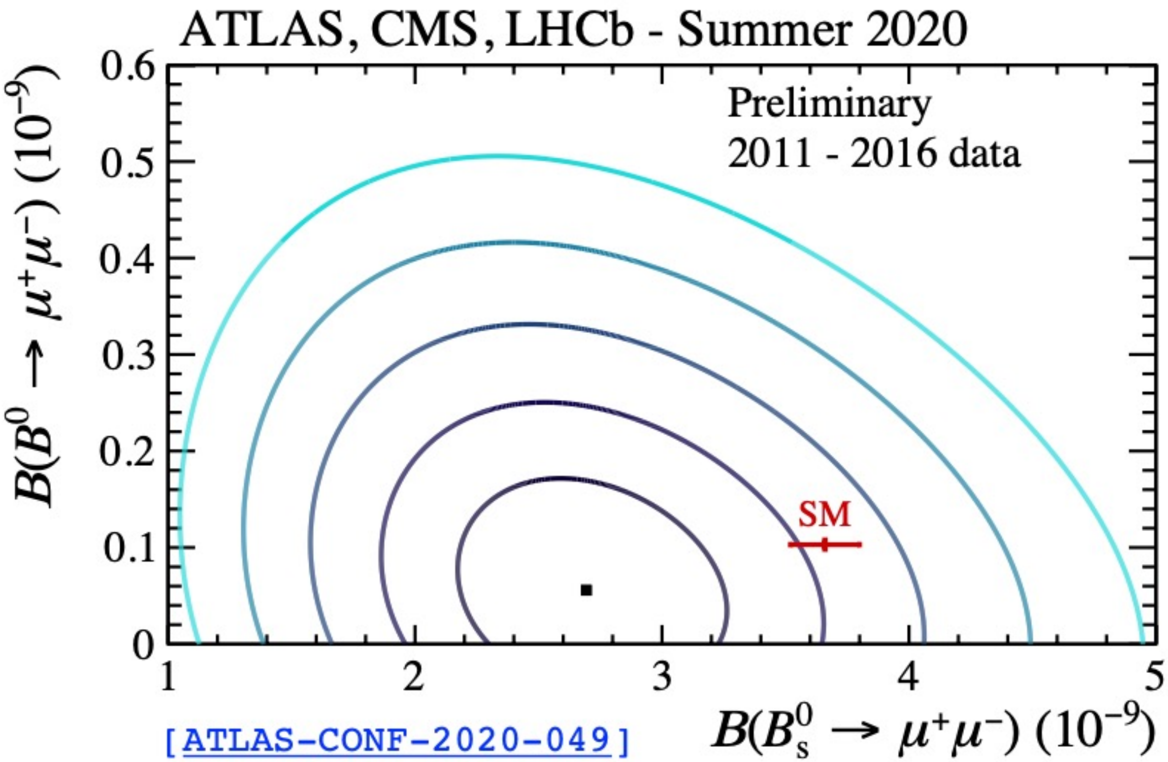




$B^0_{(s)} \to \mu^+\mu^-$, recent results

- $B^0_s \to \mu^+\mu^-$ 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



[ATLAS-CONF-2020-049]

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

- B_s^0 mixing $\Rightarrow$ effective τ

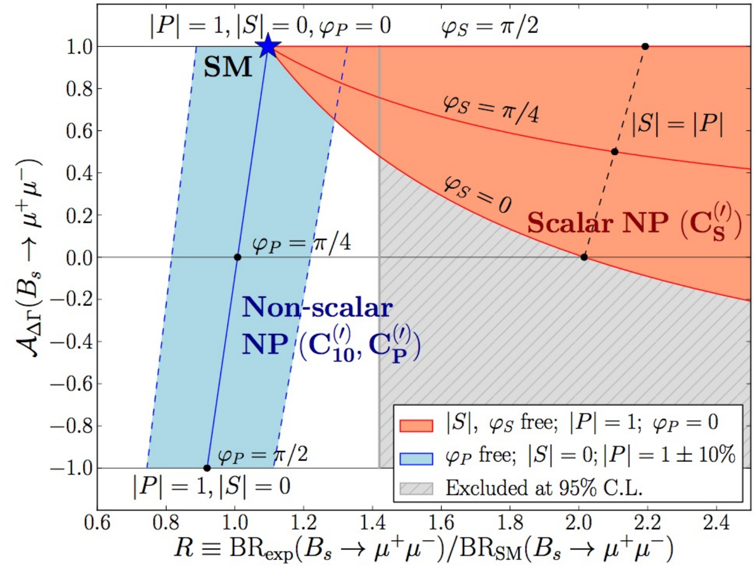
$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2A_{\Delta\Gamma}^{\mu^+\mu^-}y_s + y_s^2}{1+A_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right]$$

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

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

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

[PRL 118 (2017) 191801]



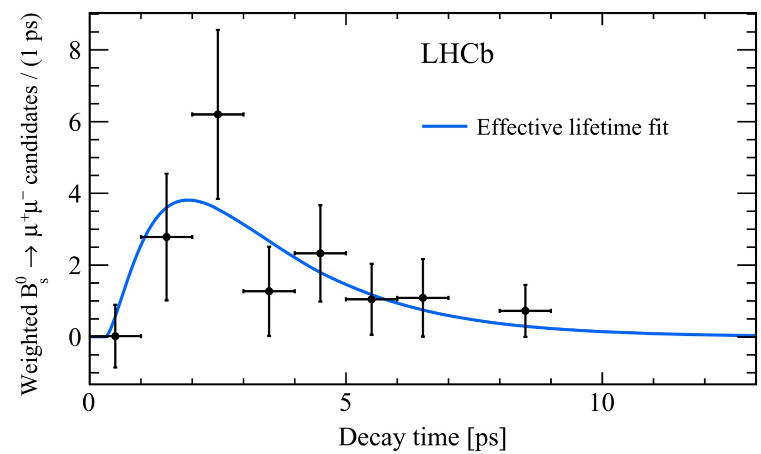
[De Bruyn *et al.*, PRL 109 (2012) 041801]

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

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

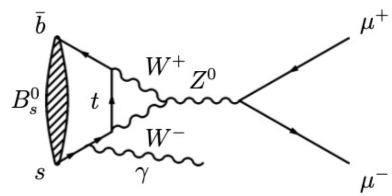
$$1.70^{+0.61}_{-0.44} \text{ ps}$$

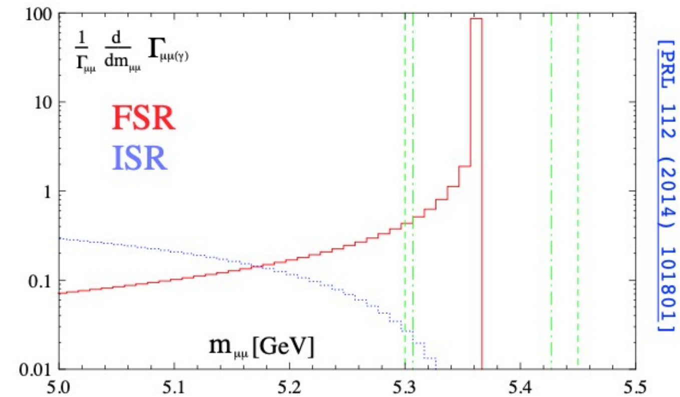
[CMS-PAS-BPH-16-004]



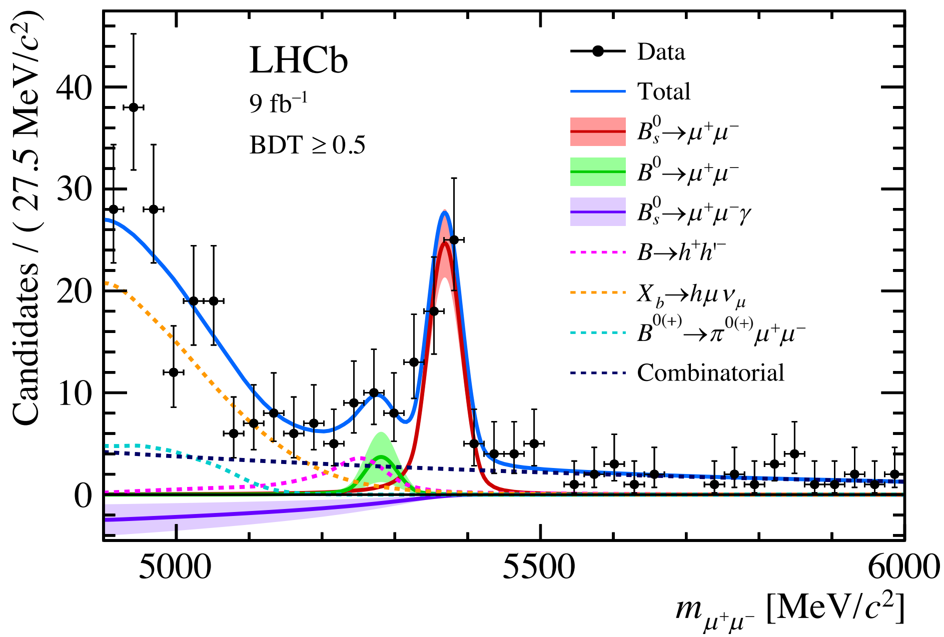
$B^0_{(s)} \to \mu^+\mu^-$

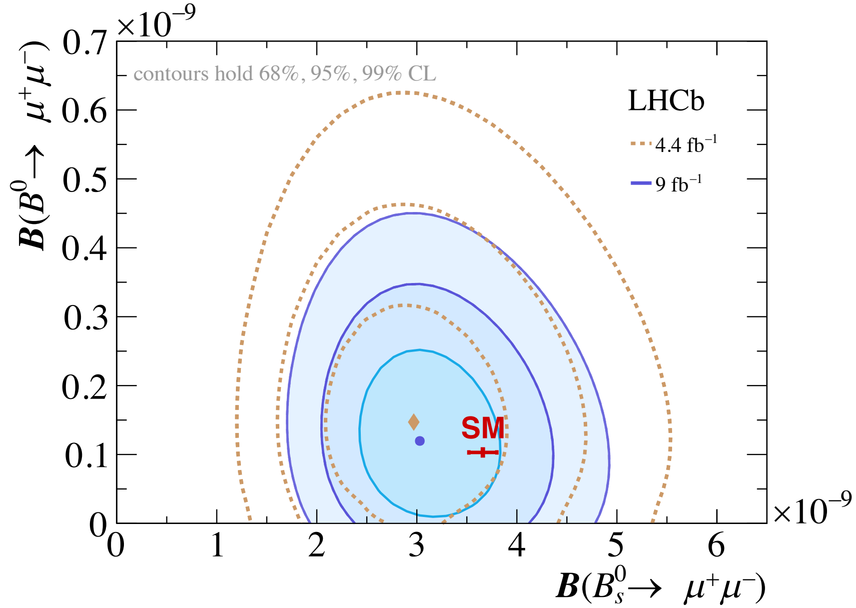
- Using all data, first limit on $B_s^0 \to \mu^+\mu^-\gamma$





[LHCb-Paper-2021-011]





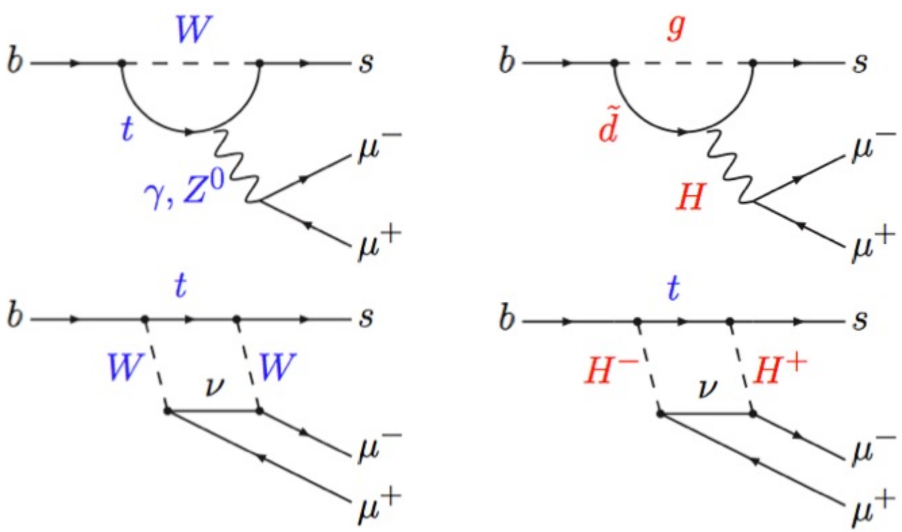
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}\ (95\,\%\ \text{CL})$$

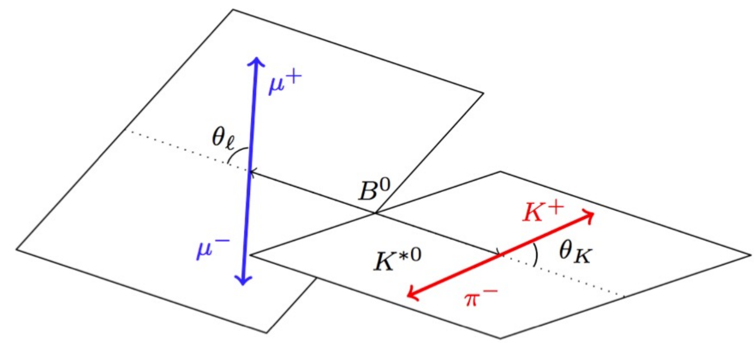
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu^+\mu^-} > 4.9\ \text{GeV}} < 2.0 \times 10^{-9}\ \ (95\,\%\ \text{CL})$$

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

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

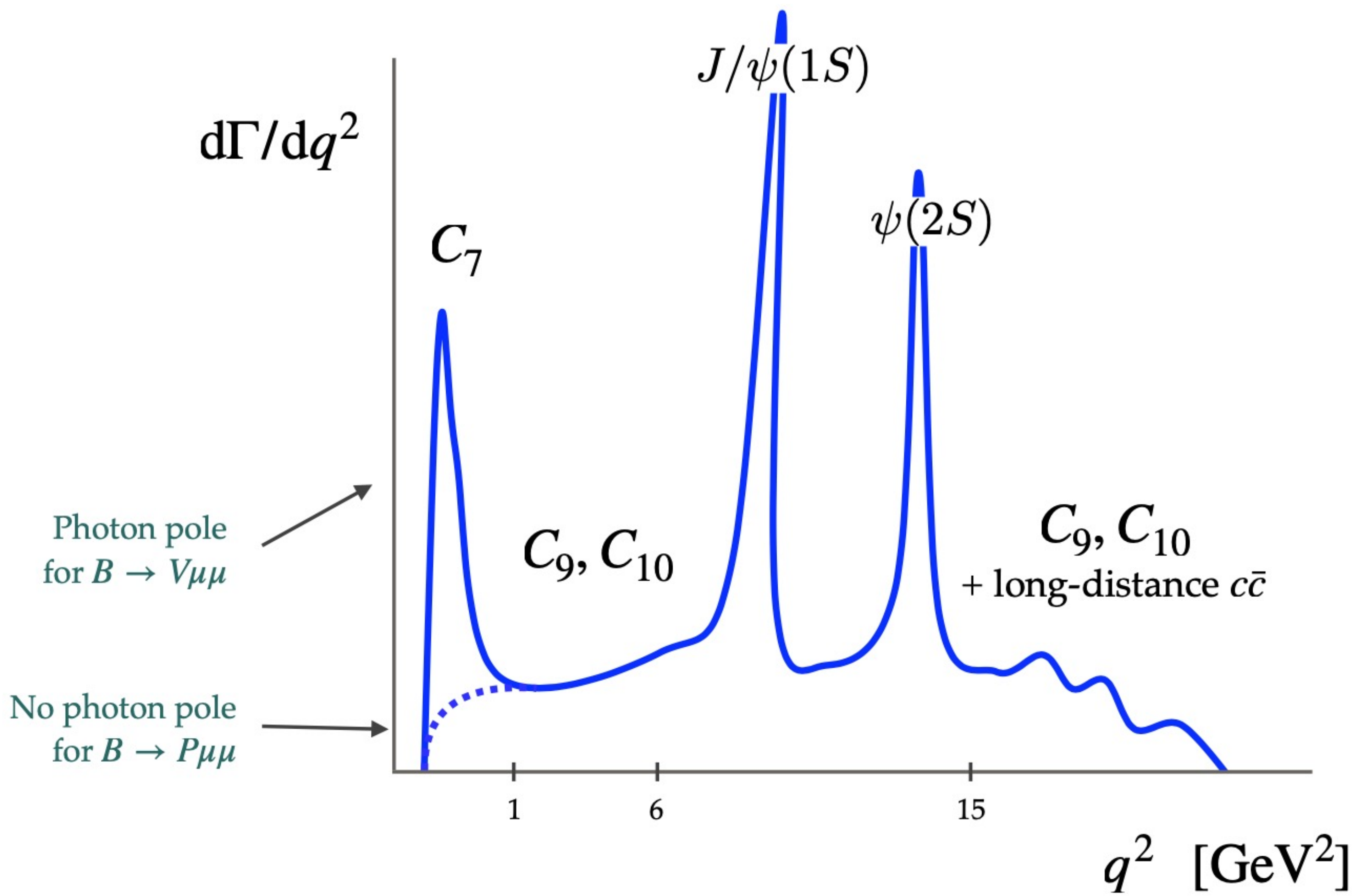
- Rates and angular distributions sensitive to NP





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

q^2 spectrum

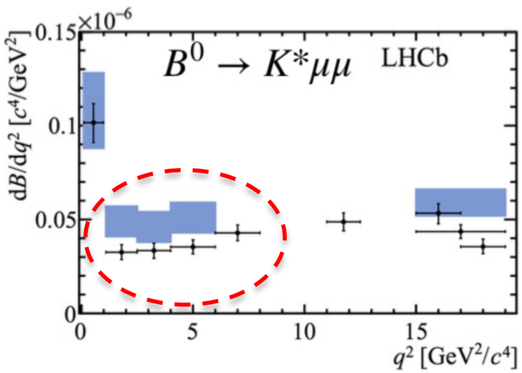


$d\Gamma/dq^2$
C_7
$J/\psi(1S)$
$\psi(2S)$
C_9, C_{10}
C_9, C_{10}
+ long-distance $c\bar{c}$
Photon pole for $B \to V\mu\mu$
No photon pole for $B \to P\mu\mu$
1
6
15
q^2 [GeV^2]

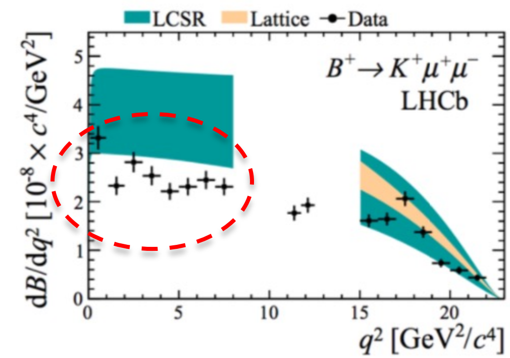
Branching fraction of $b \to s\ell^+\ell^-$

- Pattern of tensions seen, theo. uncertainty?

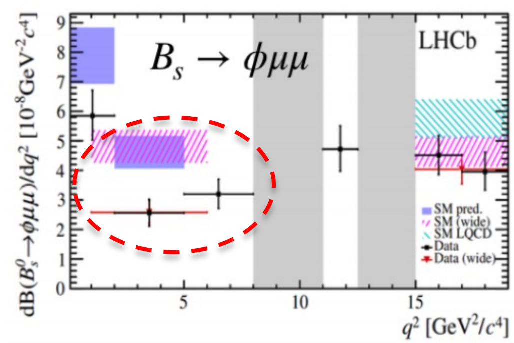
JHEP 11 (2016) 047



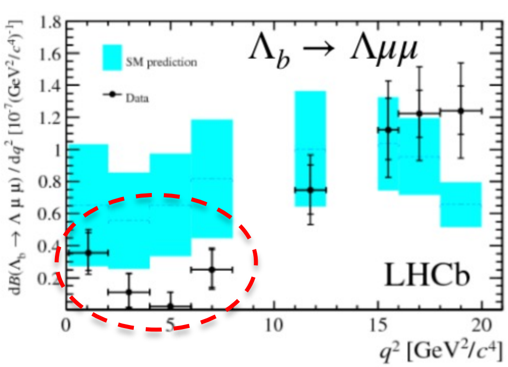
JHEP 06 (2014) 133



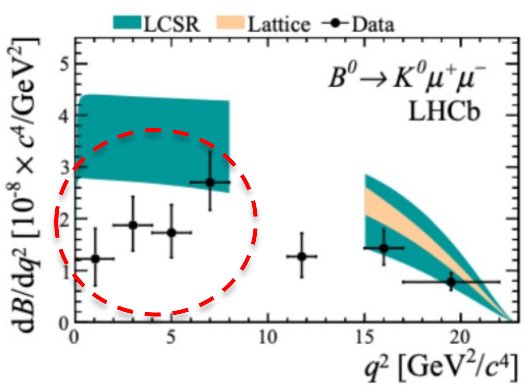
JHEP 09 (2015) 179



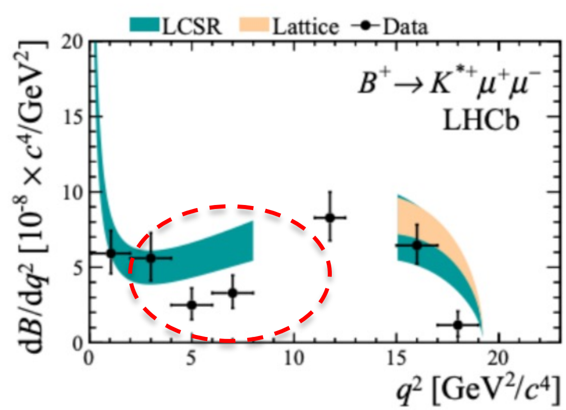
JHEP 06 (2015) 115



JHEP 06 (2014) 133



JHEP 06 (2014) 133

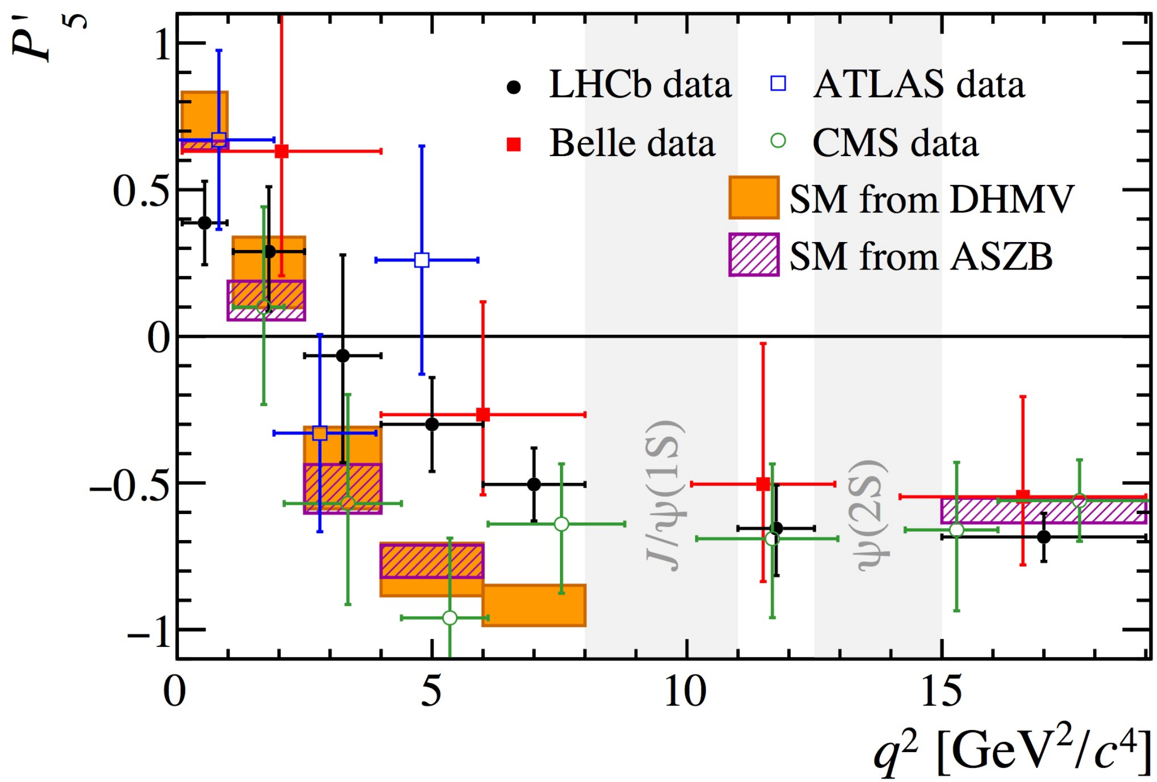


P_5' with $B^0 \to K^{*0}\mu^+\mu^-$

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

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

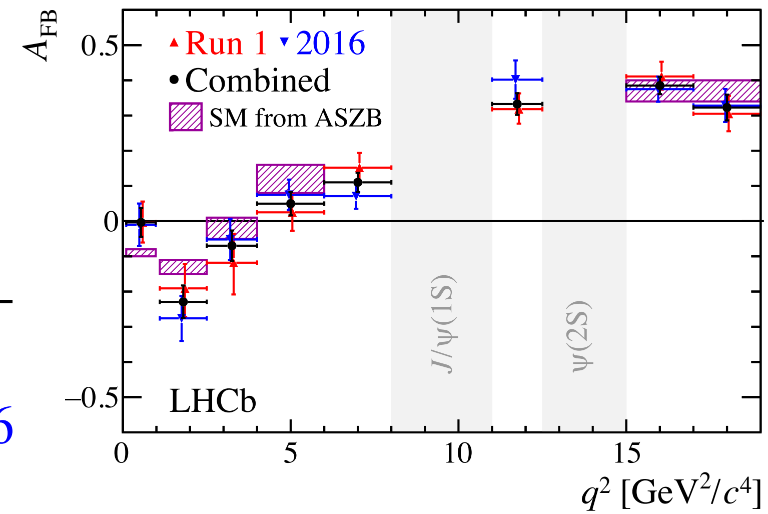
- Also measured by Belle, ATLAS, CMS



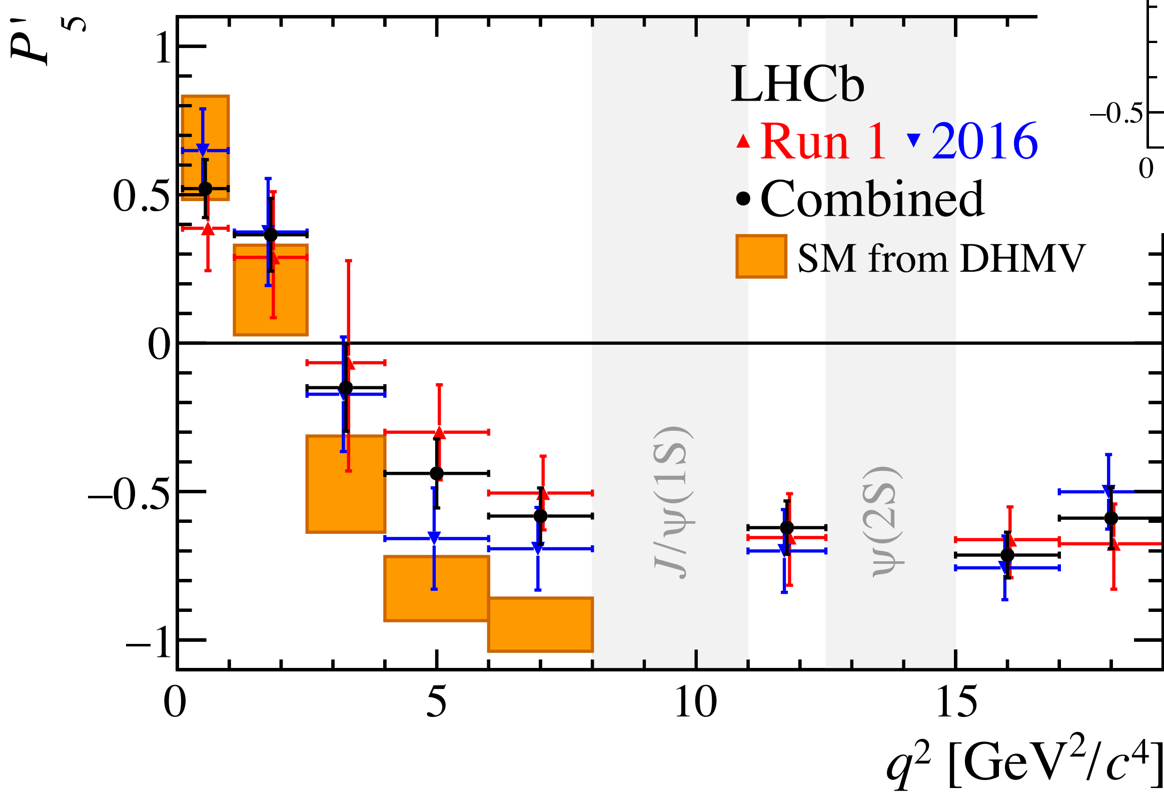
[LHCb, JHEP 02 (2016) 104]
[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

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

- Updated with 2016 data



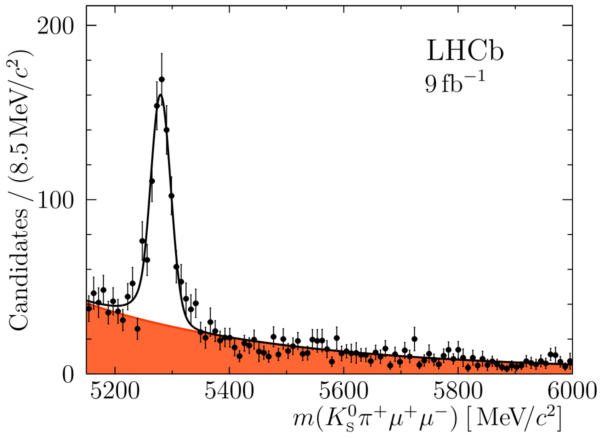
[PRL 125 (2020) 011802]

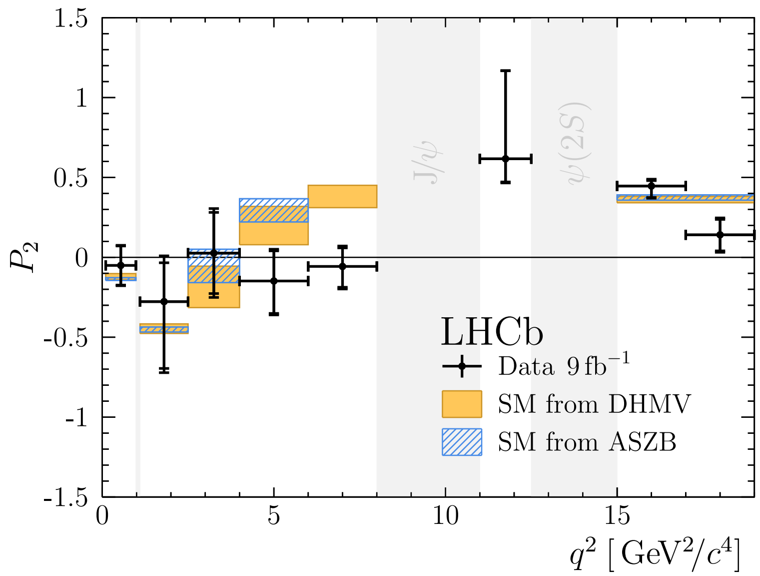


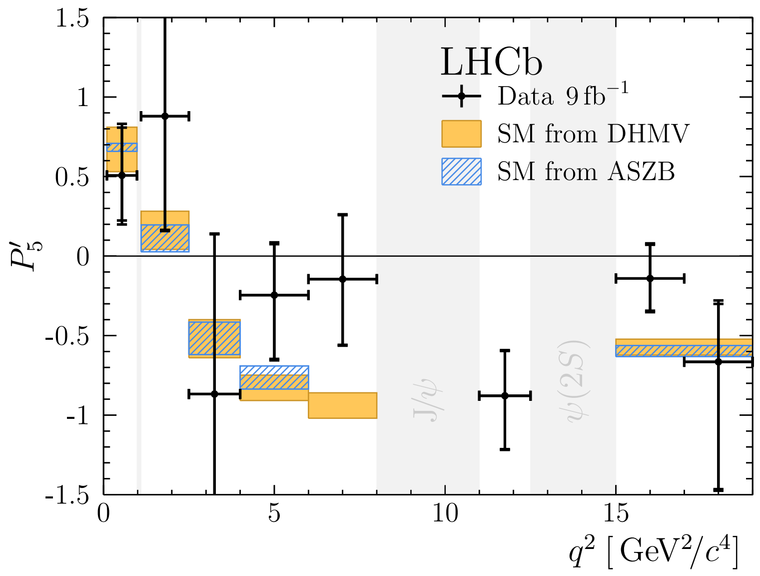
$P'_{5,2}$ with $B^+ \to K^{*+}\mu^+\mu^-$

[arXiv:2012.13241]

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

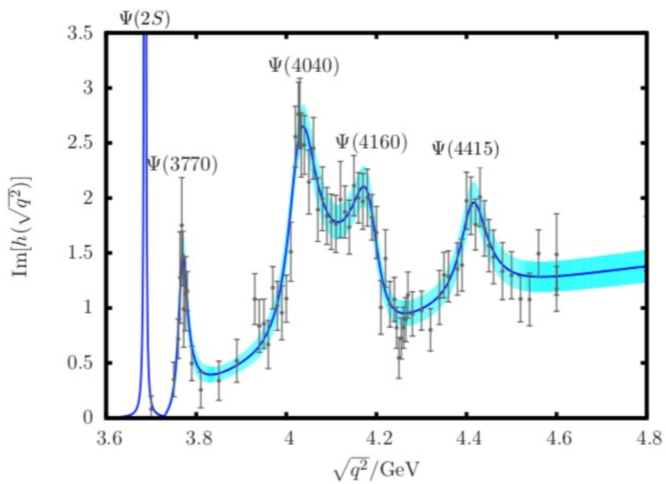


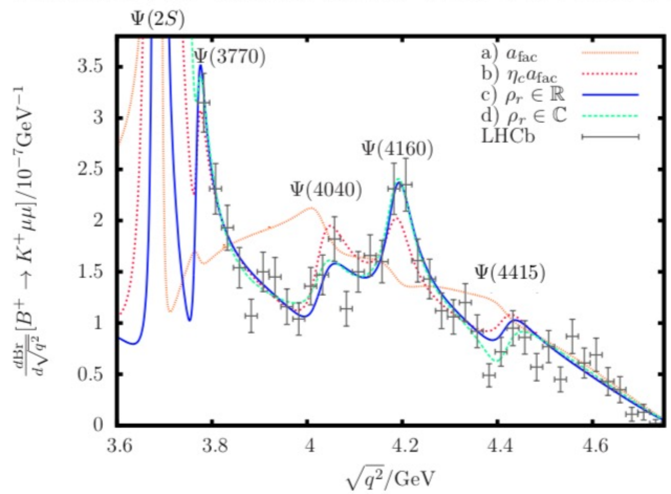




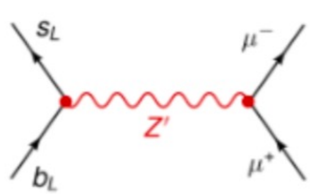
New physics, or QCD?

- 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

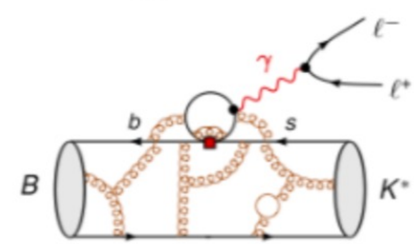




Optimist's view point

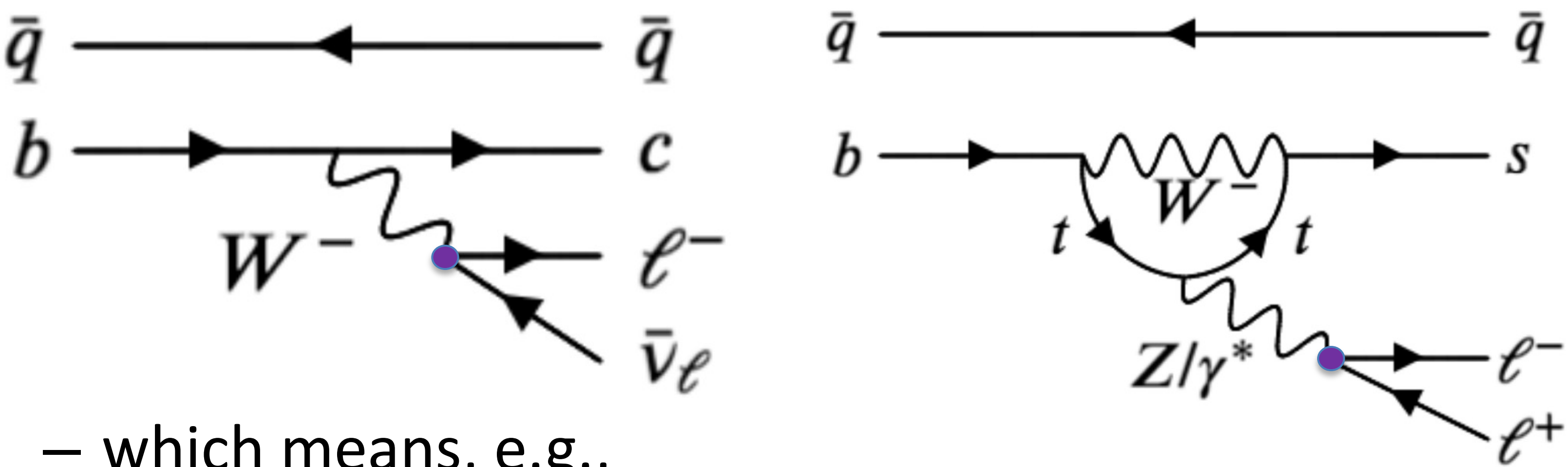


Pessimist's view point



Lepton flavor universality

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



  – which means, e.g.,

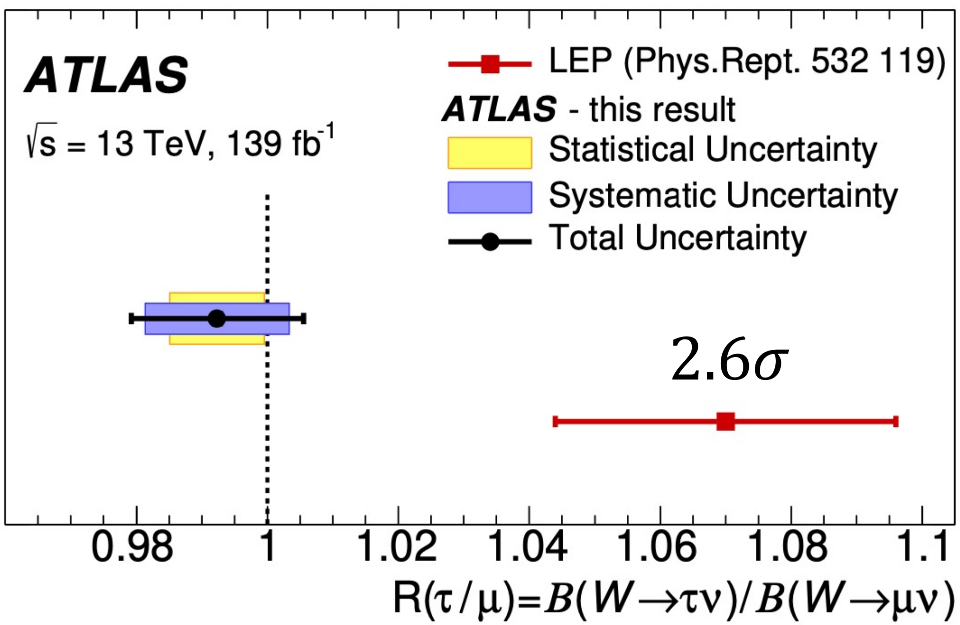
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1$$

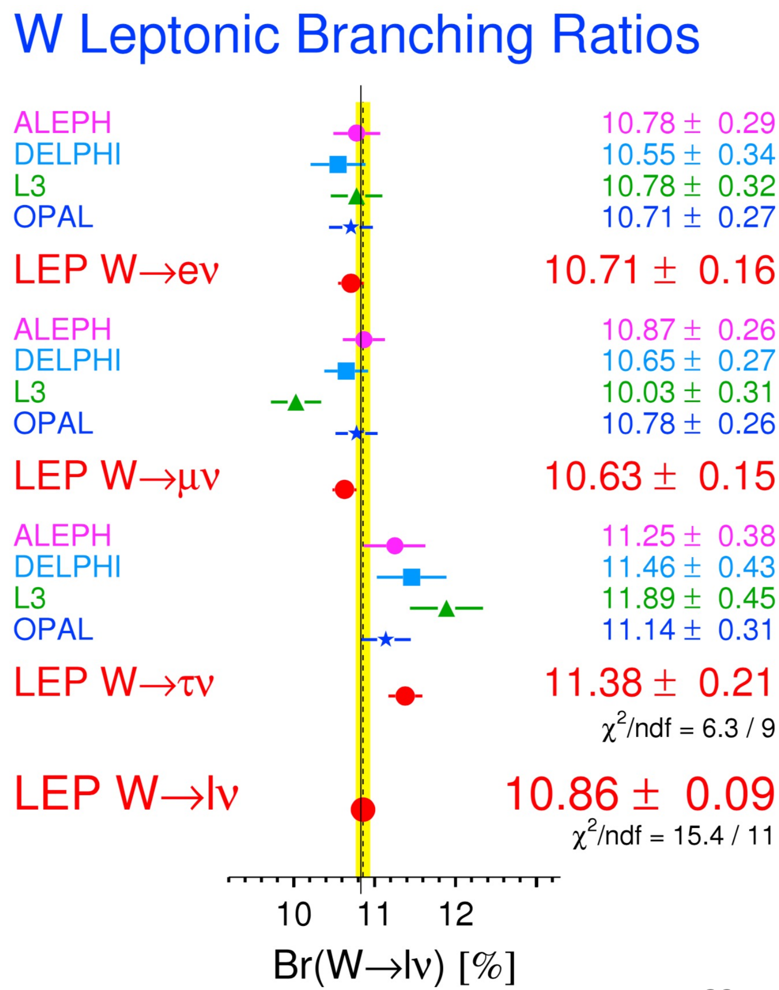
- Lepton flavor universality violation? New Physics!

Experimental test of LFU

- Well established in SM, e.g. *W->lv*
  - Some tension at LEP, addressed by ATLAS

[arXiv:2007.14040]



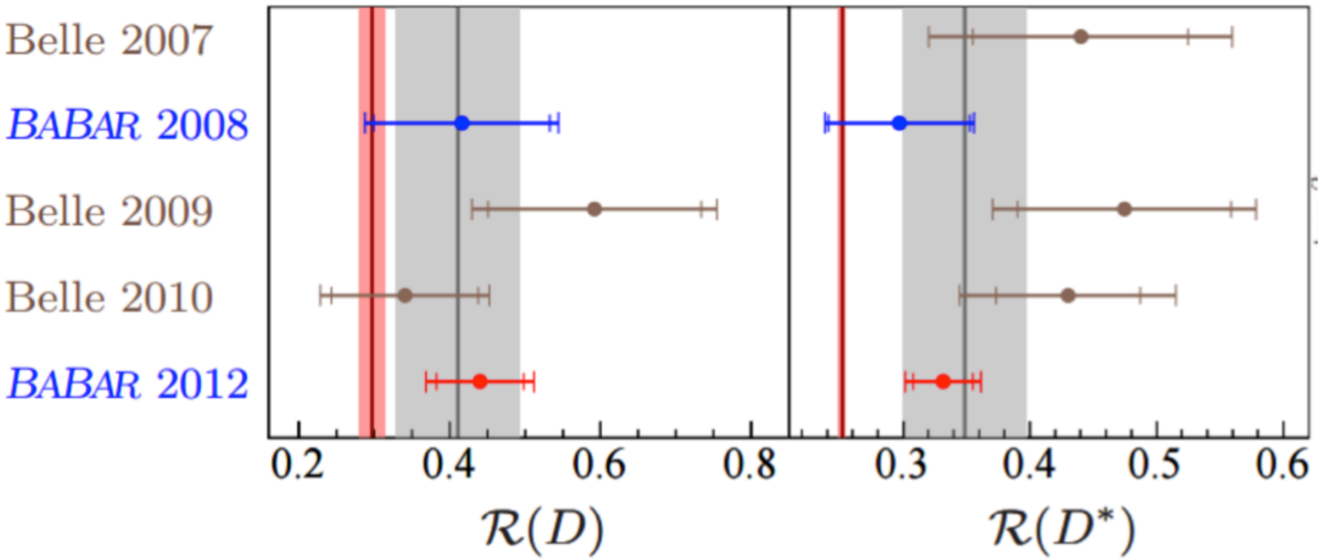


LFU in B system, pre-LHCb

- $R(D^{(*)})$, 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]



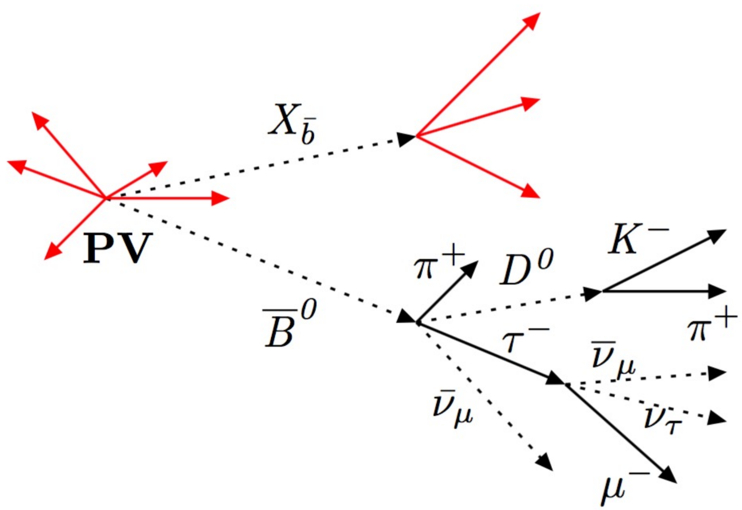
- No deviation seen in FCNC b->sll decays

R(D*) using munoic τ decays

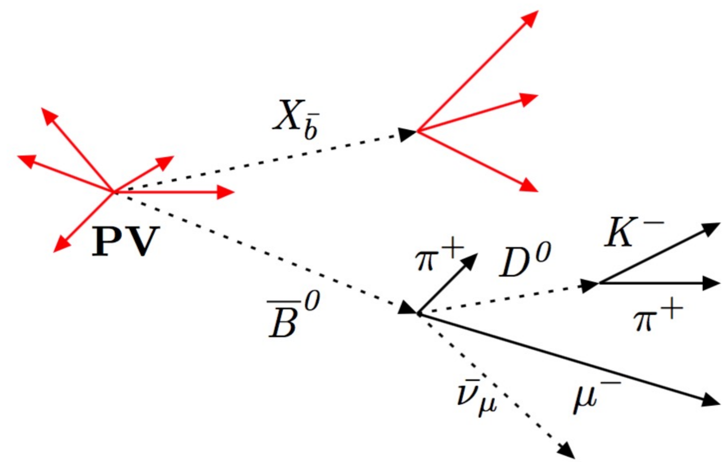
- Measure R(D*) using munoic τ decays
  - Pros: $\mathcal{B}$(τ->μX)~17.4%, B vertex rec'ible
  - Cros: no τ vertex

[PRL 115 (2015) 118003]

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



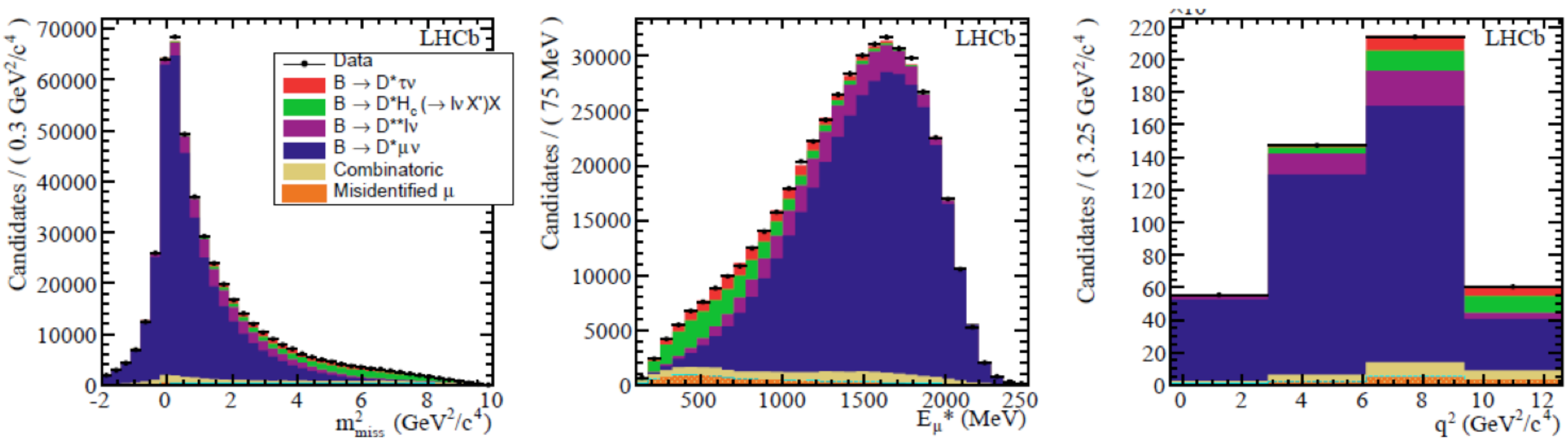
Normalisation $(B^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$



R(D*), results

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

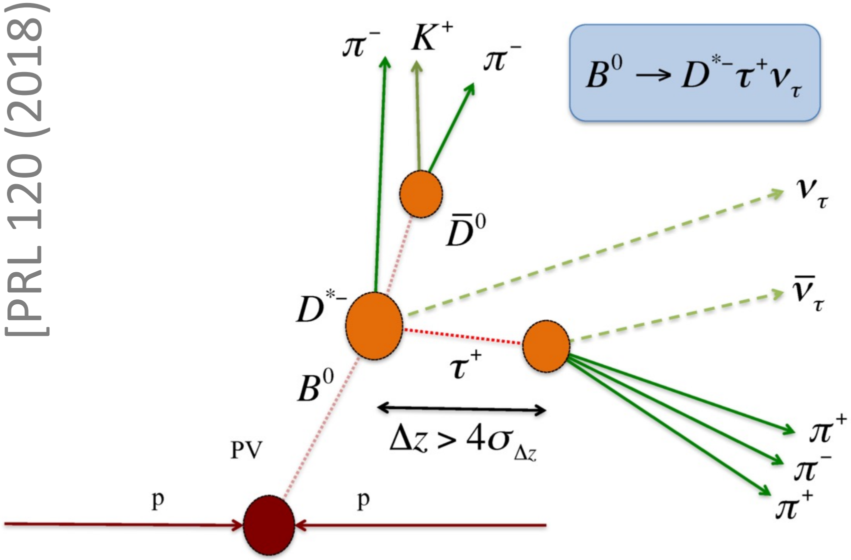
[PRL 115 (2015) 118003]

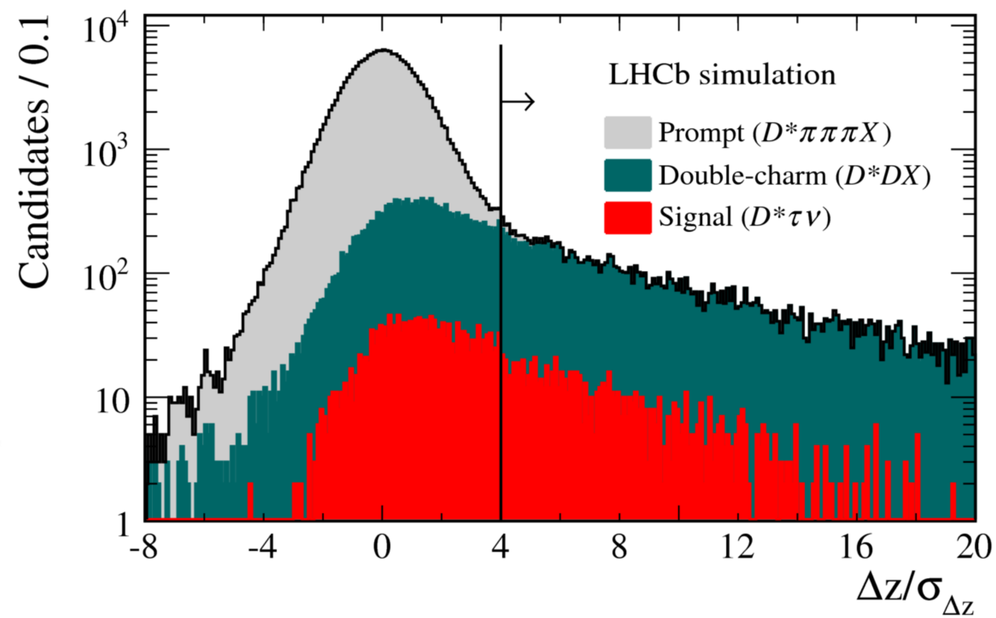


R(D*) using 3-prong τ decays

- Measure R(D*) using 3-prong τ decays
  - Pros: $\mathcal{B}(\tau\to3\pi^{\pm}X)$~9%+4%(≥1$\pi^0$), B/τ vertex rec'ible
  - Cros: soft $\pi^{\pm}$, bkg; different from norm. decay

[PRL 120 (2018) 171802]





R(D*), results

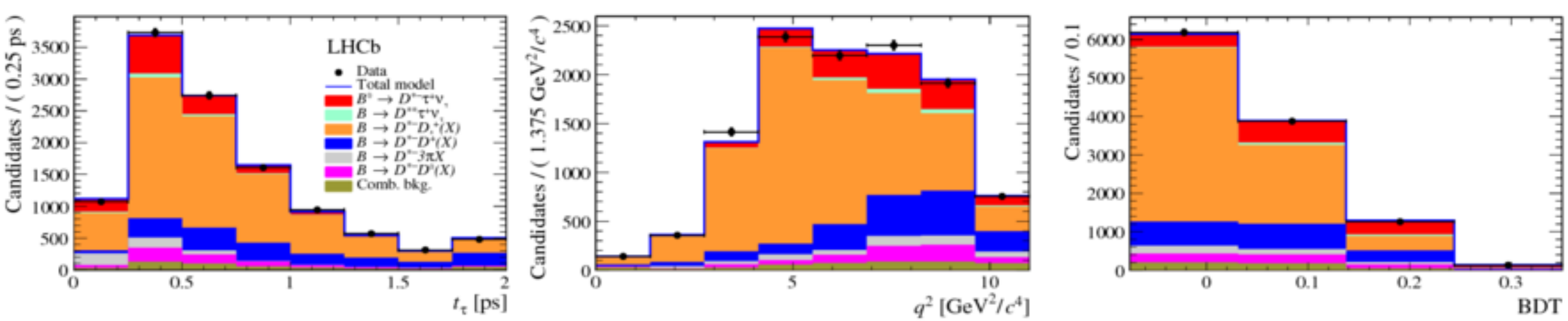
- Normalized to $B^0 \to D^{*-}3\pi$

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

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

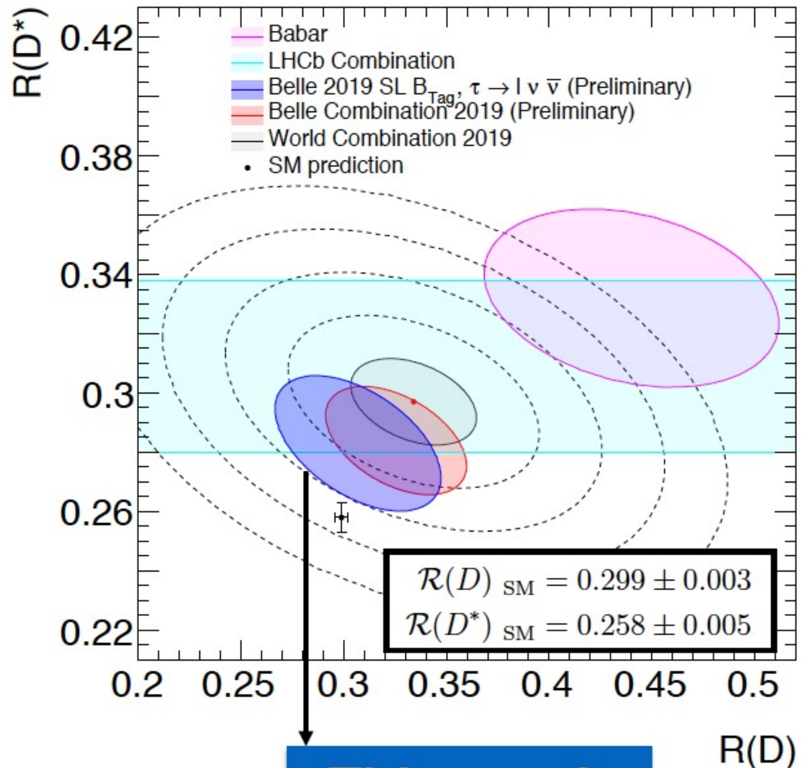
    c.f. muonic: 16 500 ± 1 670

[PRL 120 (2018) 171802]



Recent update from Belle

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



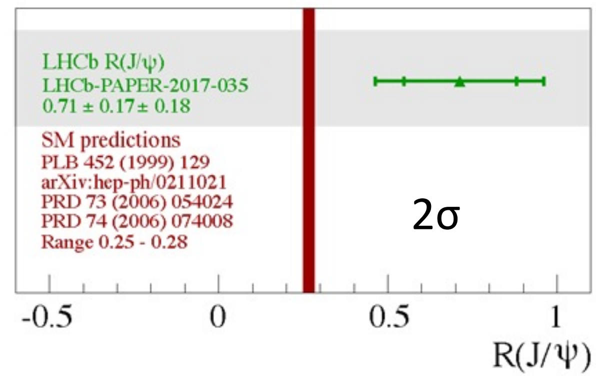
This result

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

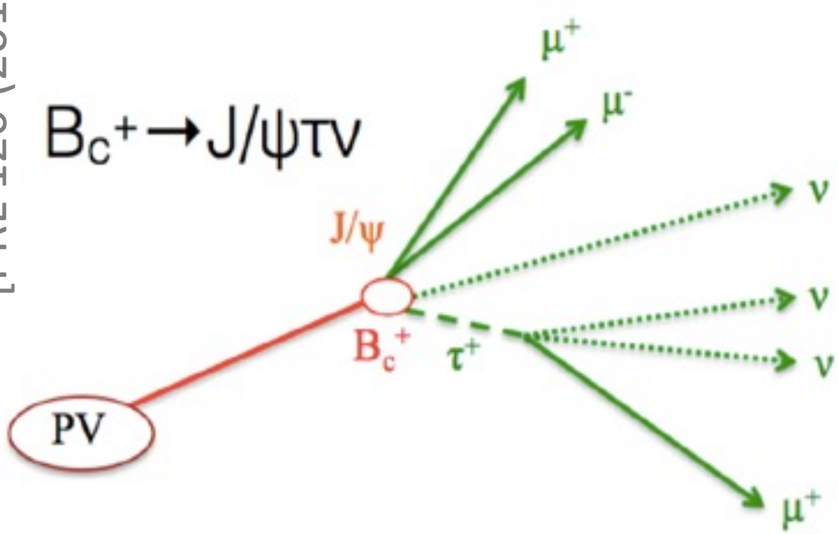
G. Caria, Moriond EW, March 19

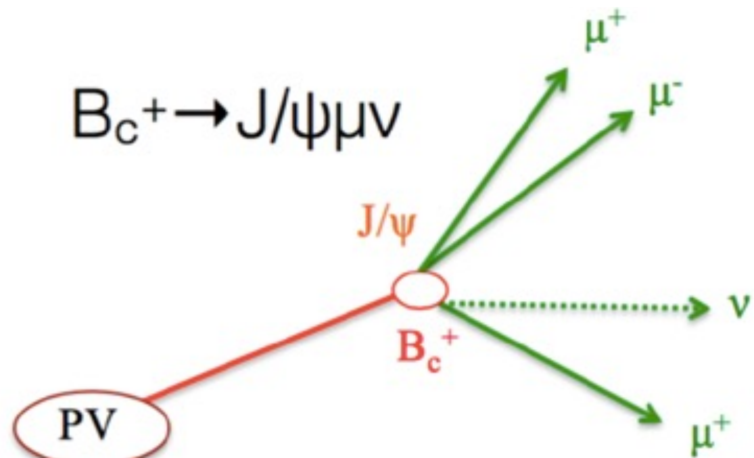
R(J/ψ) using munoic τ decays

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



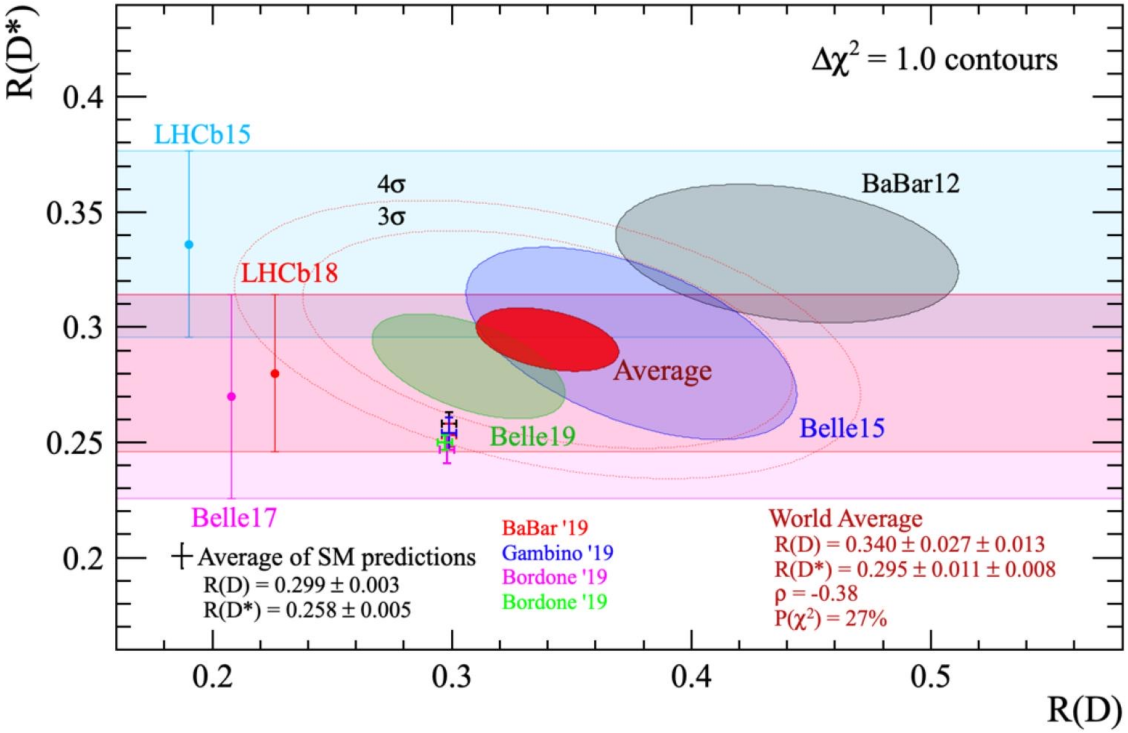
[PRL 120 (2018) 121801]

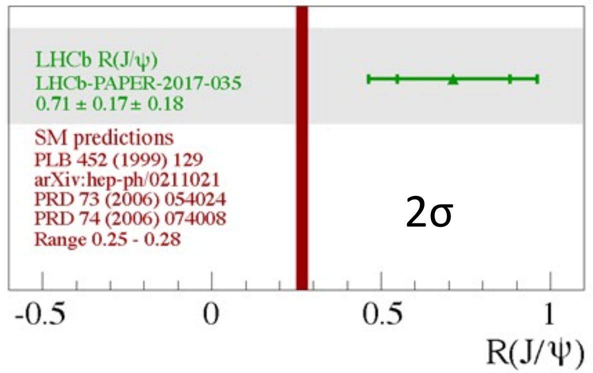




Summary of LFU in b->clv decays

- Deviations from SM seen by Babar/Belle/LHCb





2σ

Back to 3.8σ?

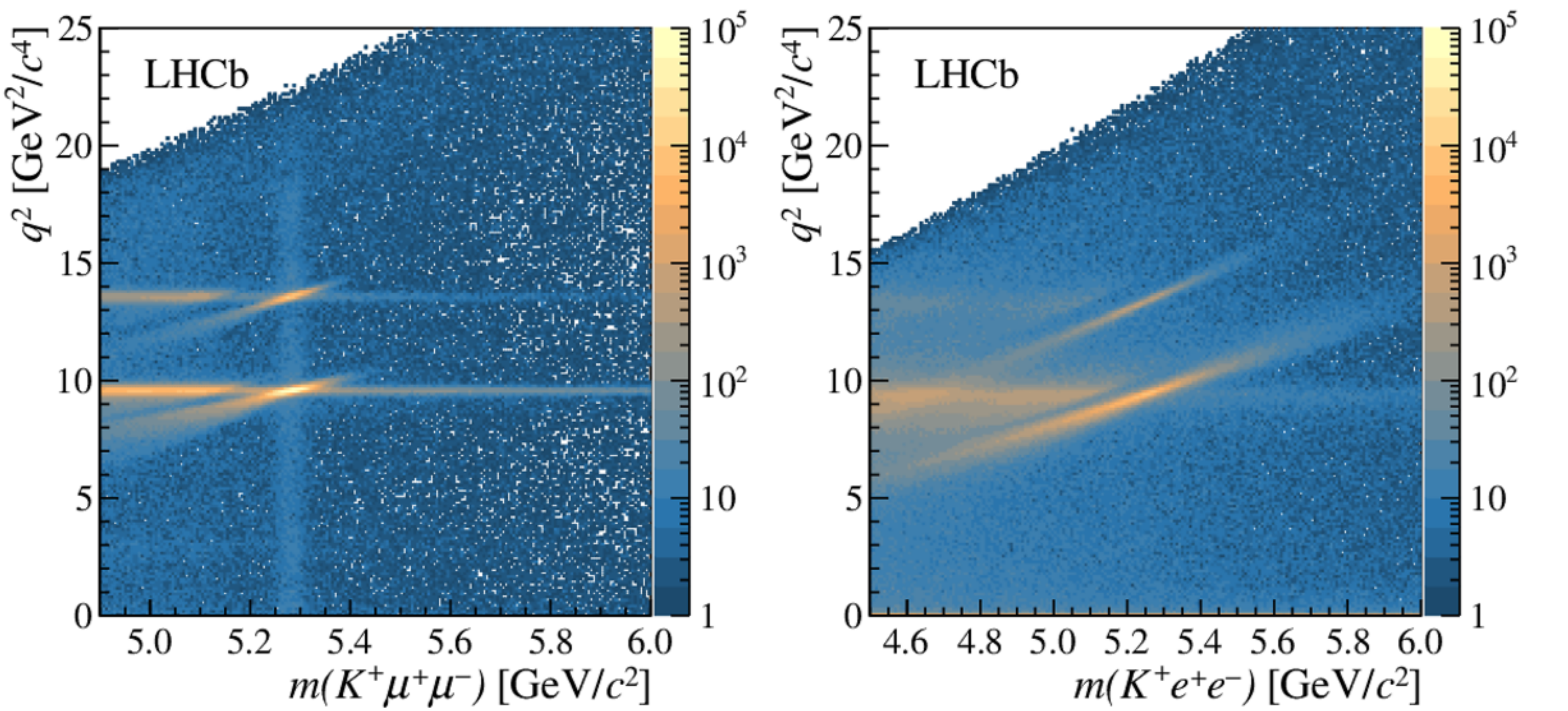
[arXiv:1912.09335]

R(K), introduction

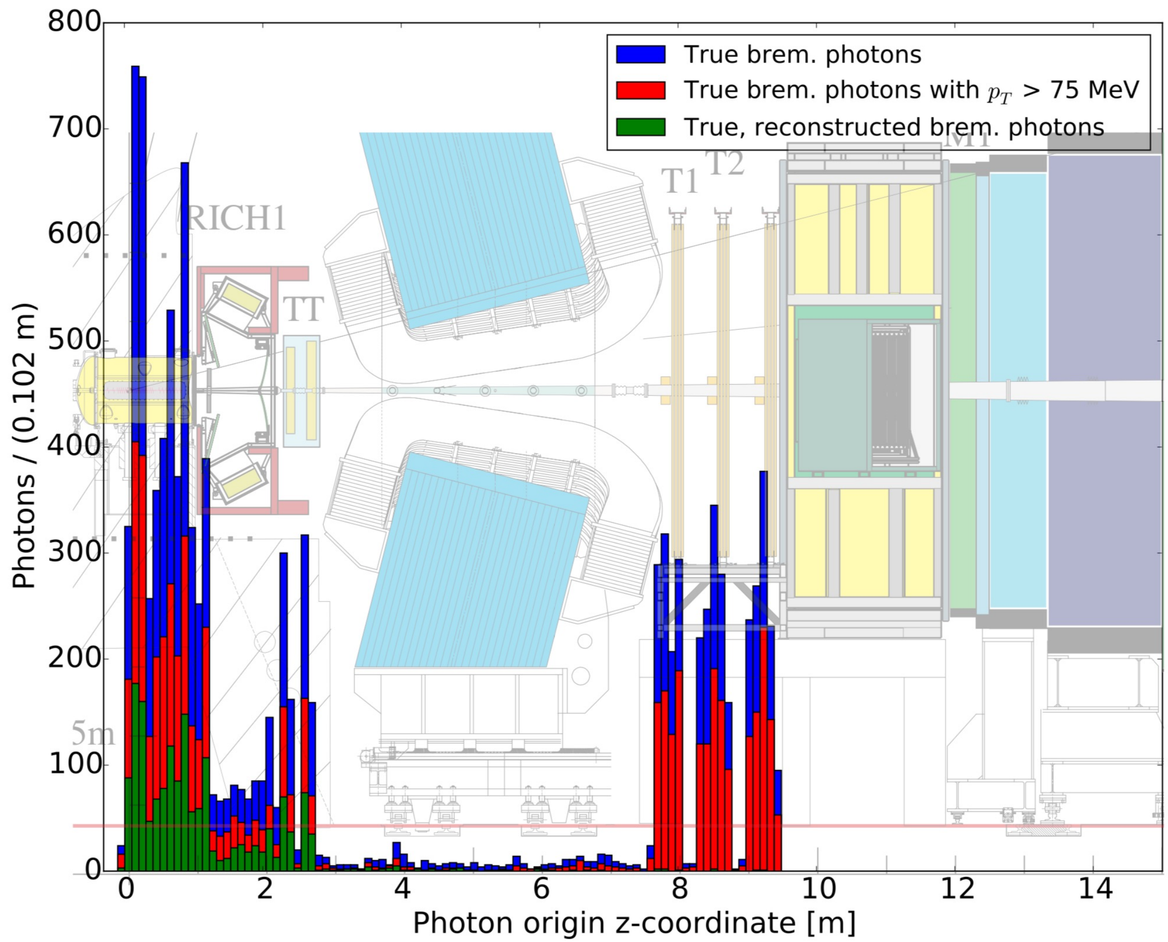
- Double ratio to control systematics

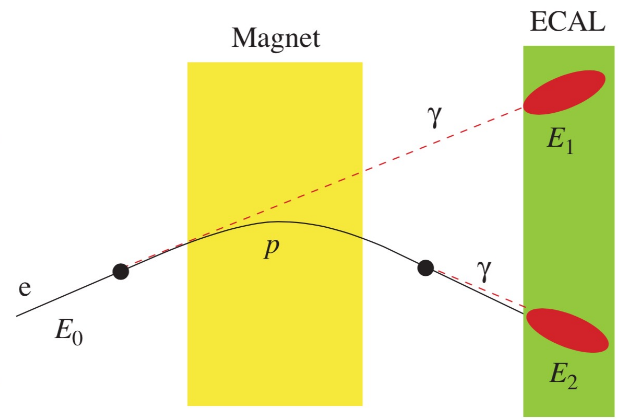
$$\mathcal{R}_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right)\left(\frac{\varepsilon_{K^+e^+e^-}}{\varepsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\varepsilon_{J/\psi(\mu^+\mu^-)K^+}}{\varepsilon_{J/\psi(e^+e^-)K^+}}\right)$$

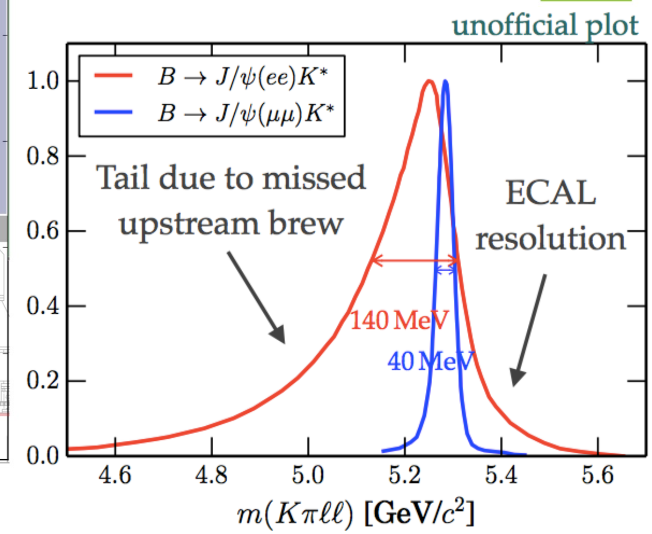
[PRL 122 (2019) 191801]



Bremsstrahlung corrections

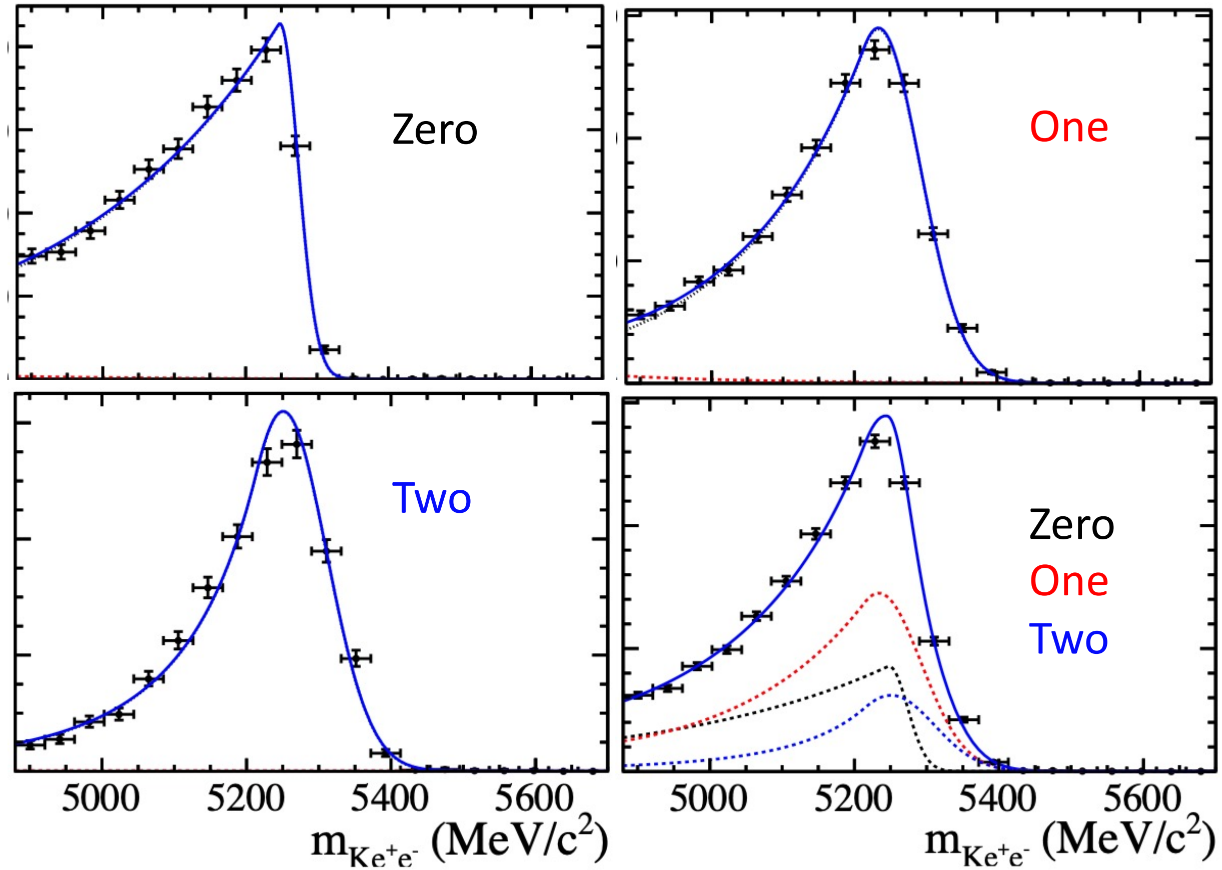






Signal line shape

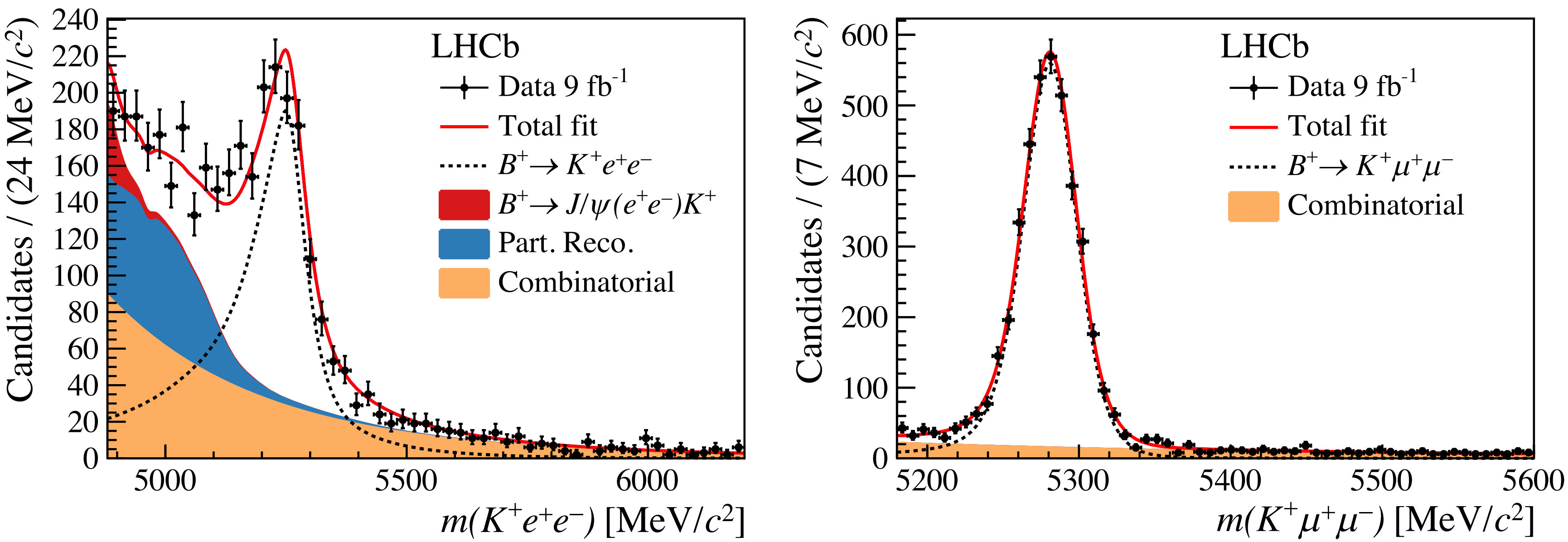
- Split acording to number of brem-photons



Signal yields with all data

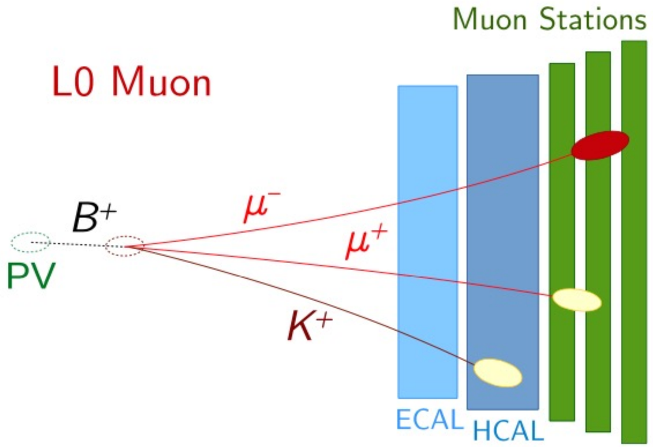
- 9 fb^{-1} of data:
  - $N(B^+ \to K^+e^+e^-) = 1640 \pm 70$
  - $N(B^+ \to K^+\mu^+\mu^-) = 3850 \pm 70$

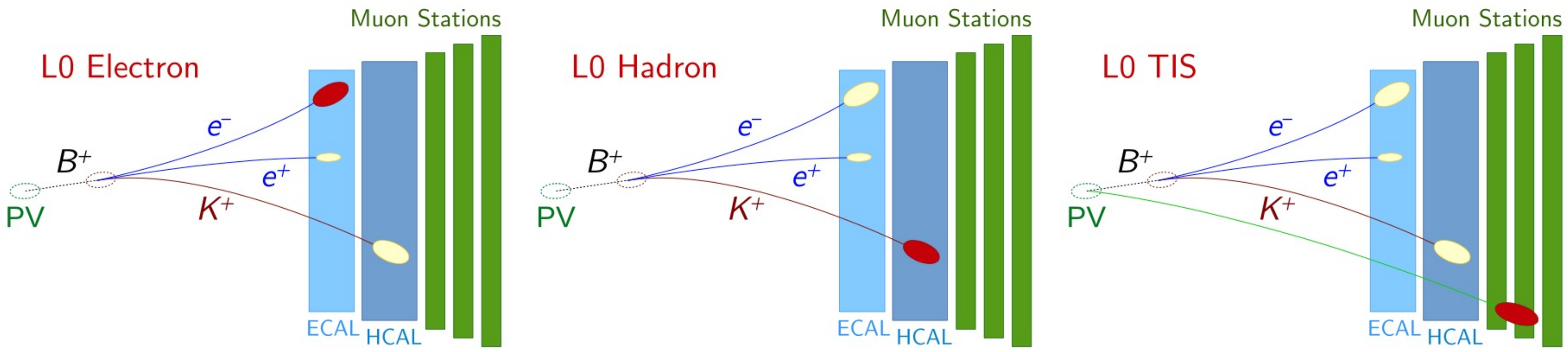
[arXiv:2103.11769]



Trigger strategy

- Trigger on signal (TOS)
- Trigger Independent of Signal (TIS)
- Bottleneck: L0/Hardware

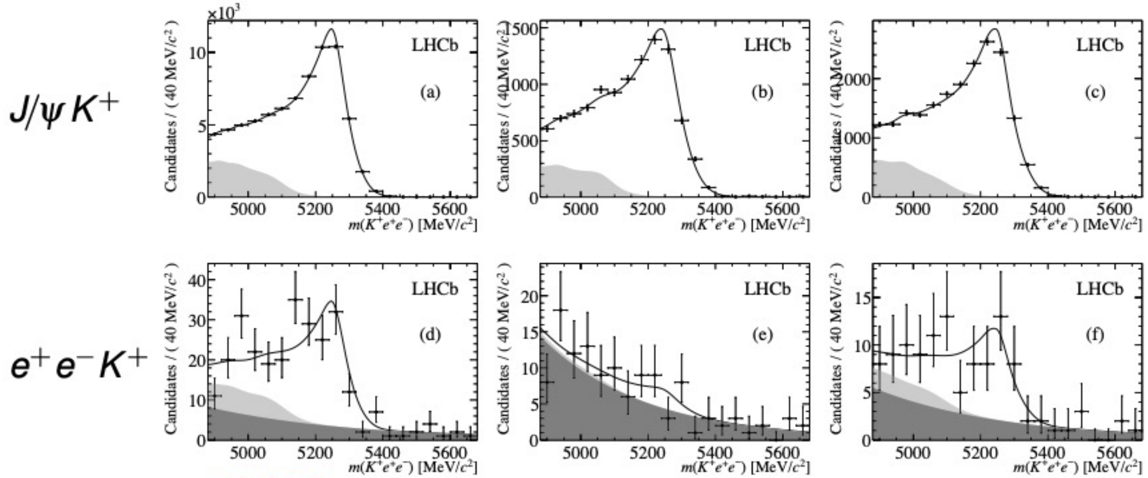




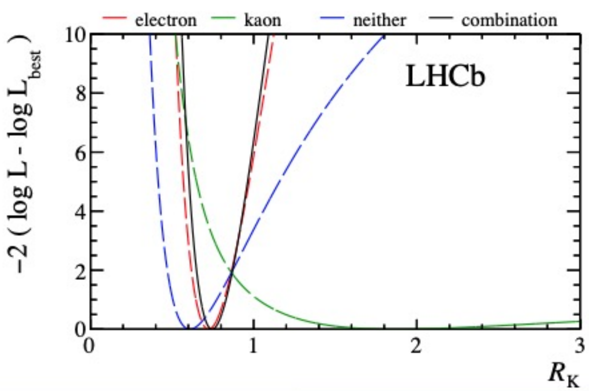
Trigger strategy (cont.)

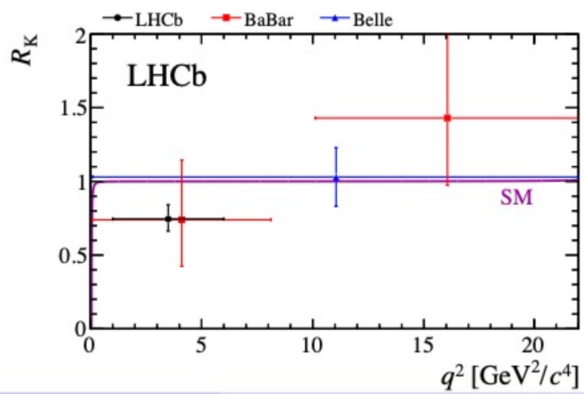
[arXiv:1406.6482]

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



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

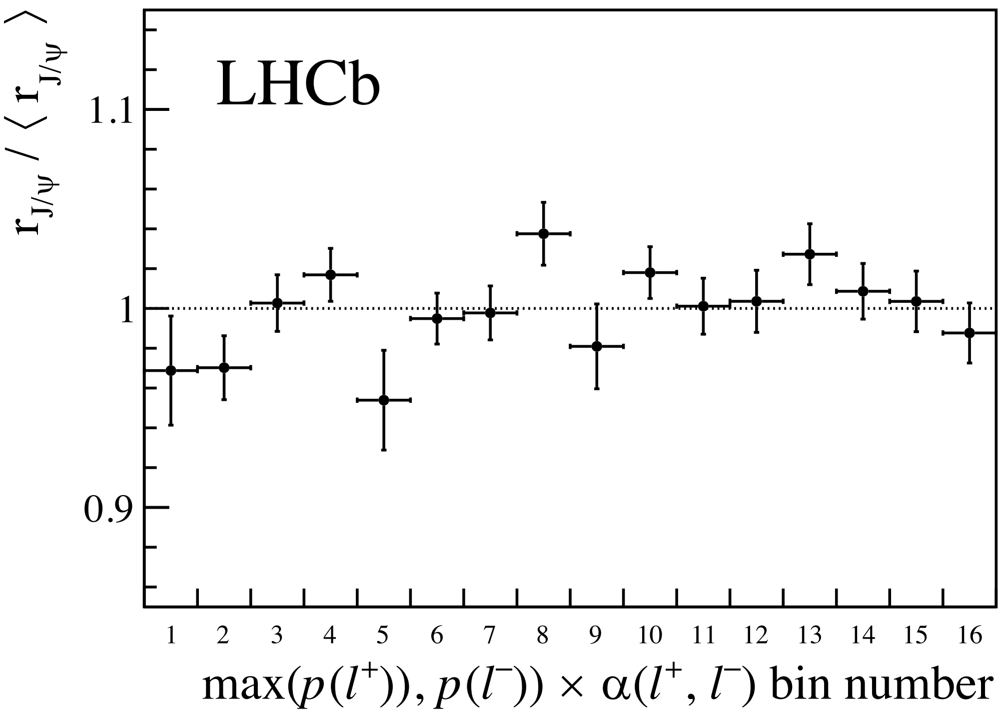


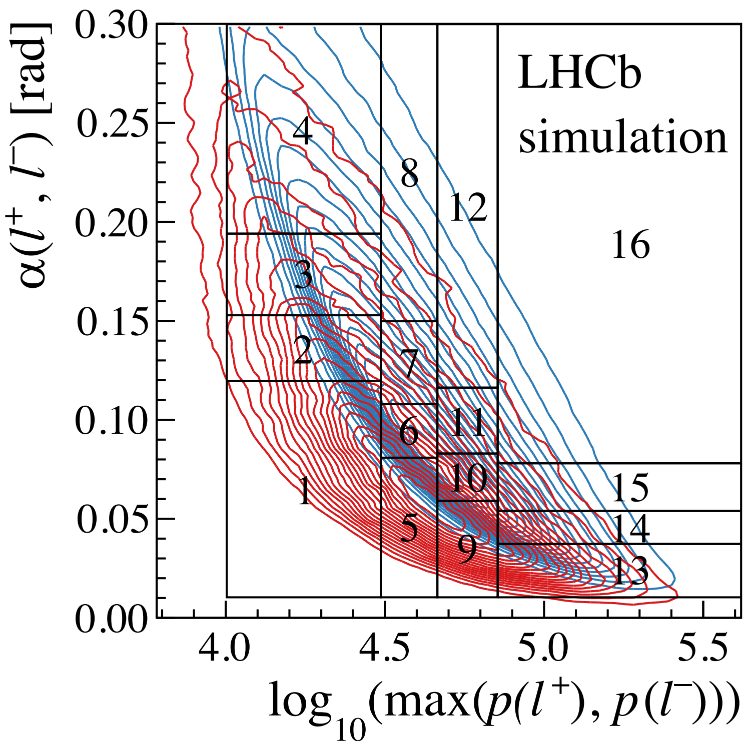


Checks on efficiency

- Flatness of $r_{J/\psi} = \frac{\mathcal{B}(B^+ \to J/\psi(\mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(e^+e^-)K^+)}$, $r_{\psi(2S)}$

[arXiv:2103.11769]

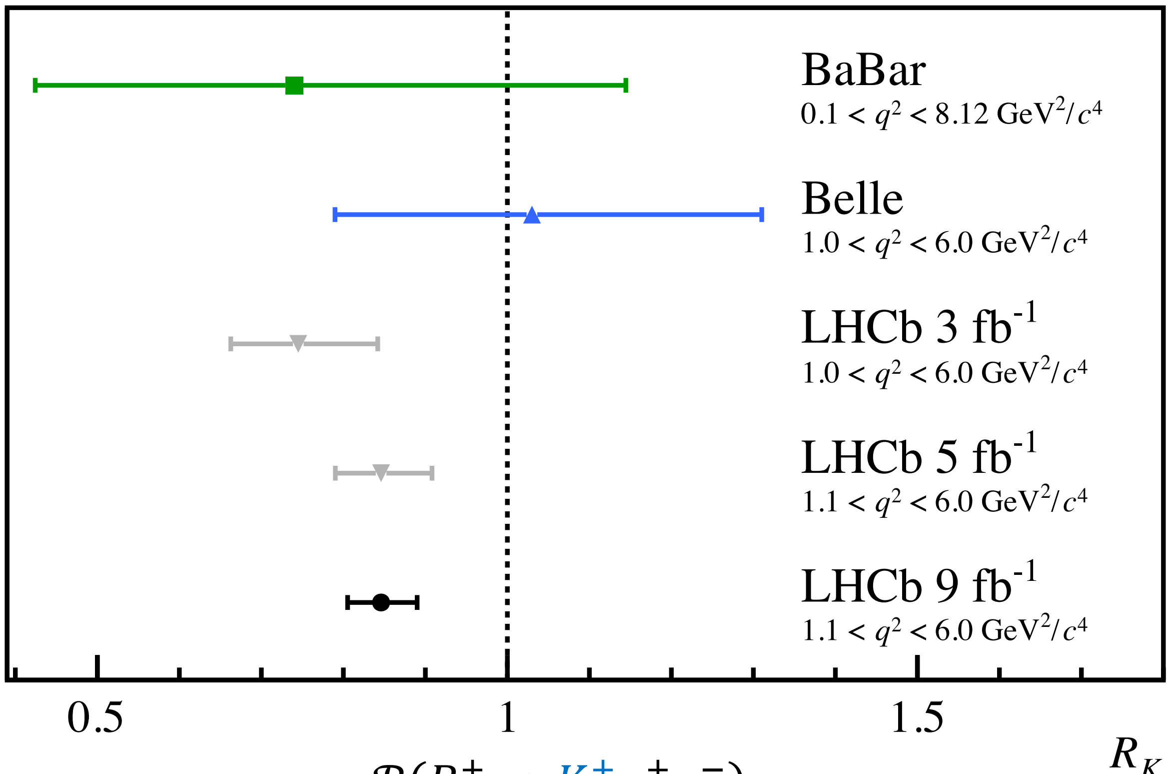




R(K), latest results

- Devivation from SM, 3.1σ by LHCb

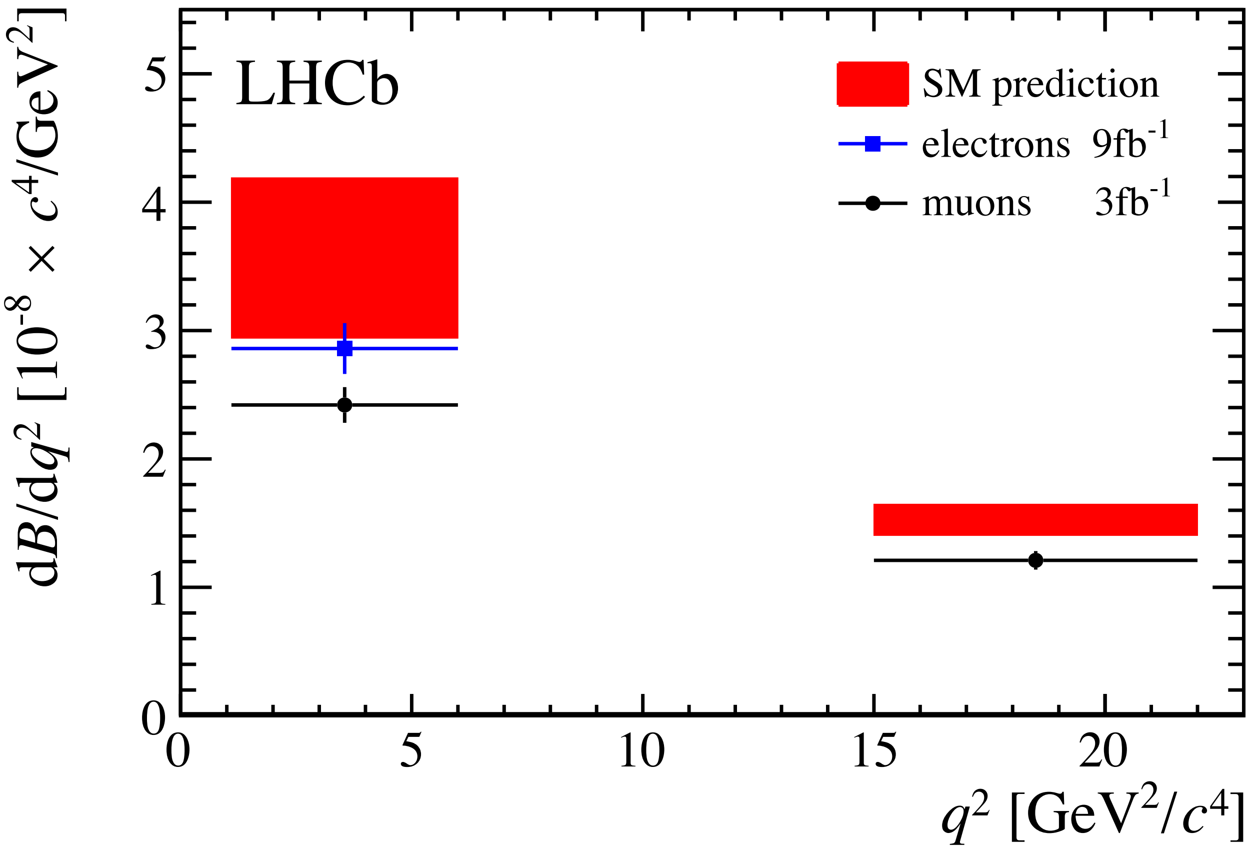
[arXiv:2103.11769]



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

From R(K) to BR

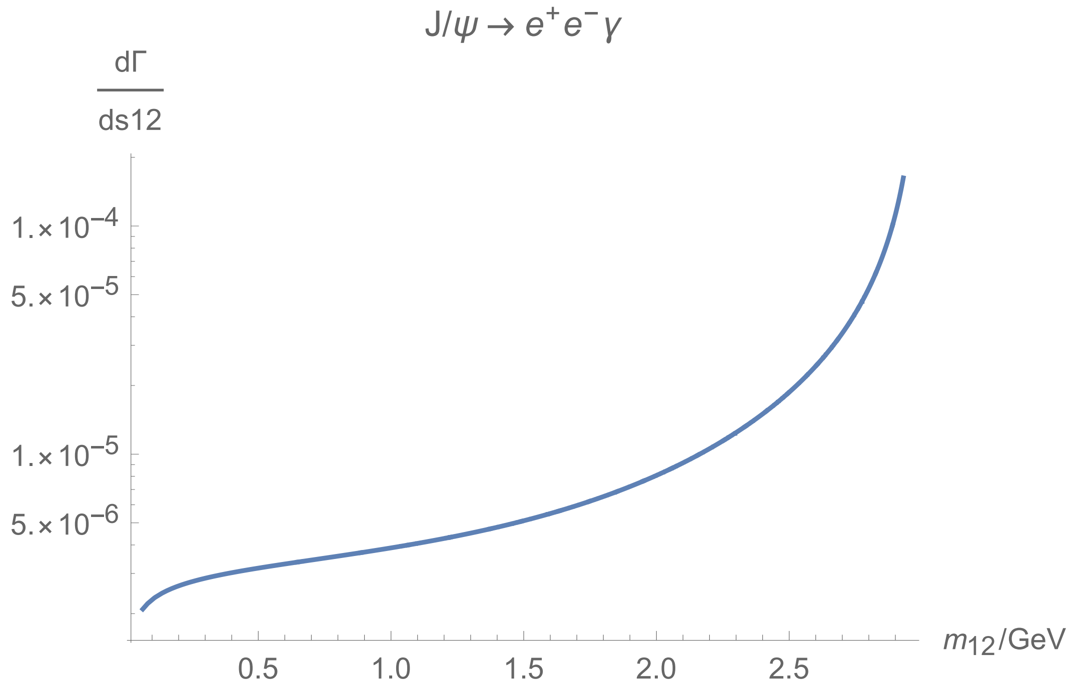
- Electron mode more close to SM prediction?



[arXiv:2103.11769]

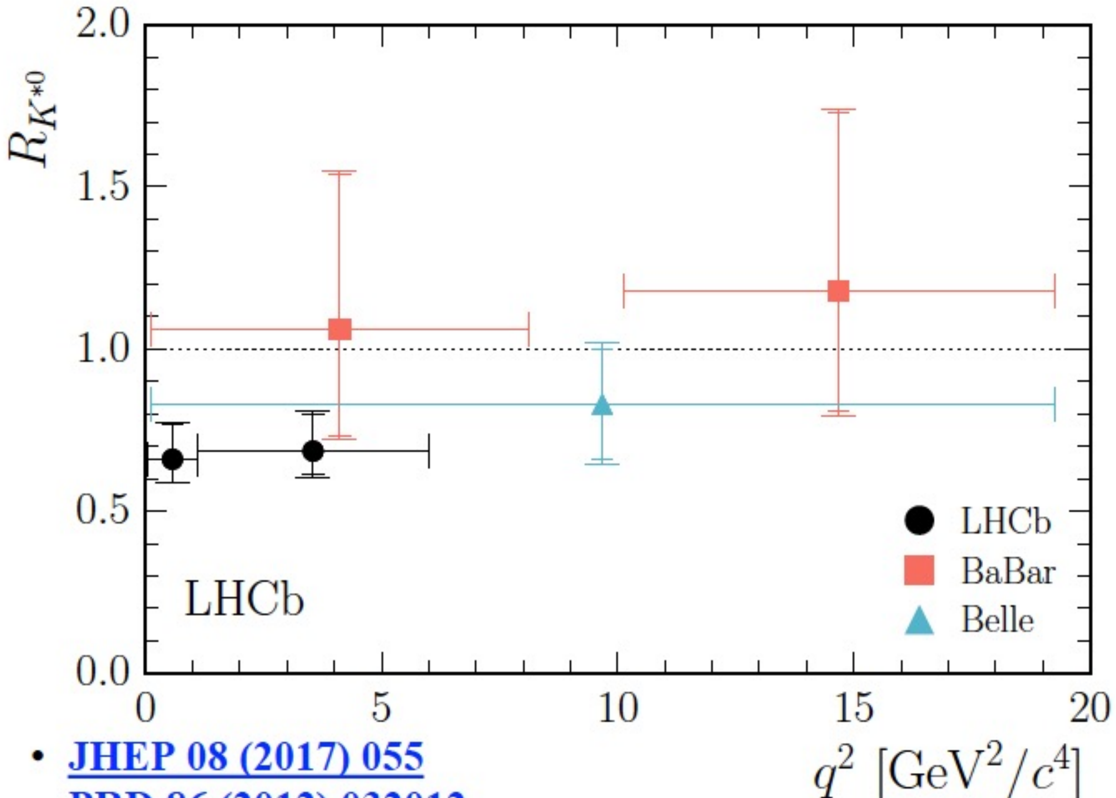
Contribution of $J/\psi \to e^+e^-\gamma$

- Synergy with BES-III
- Theoretical calculation by Jichen Pan & Yu Jia



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

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

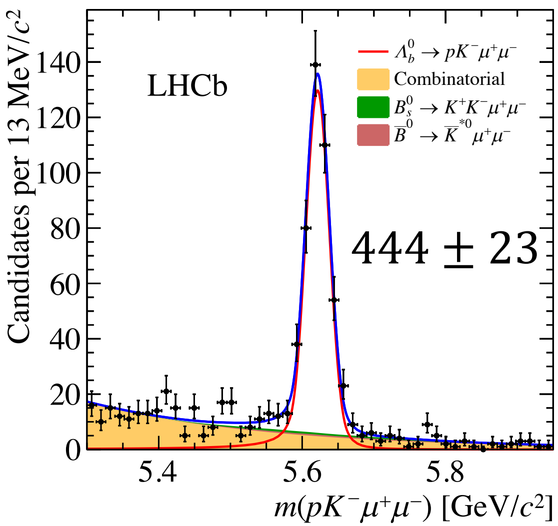


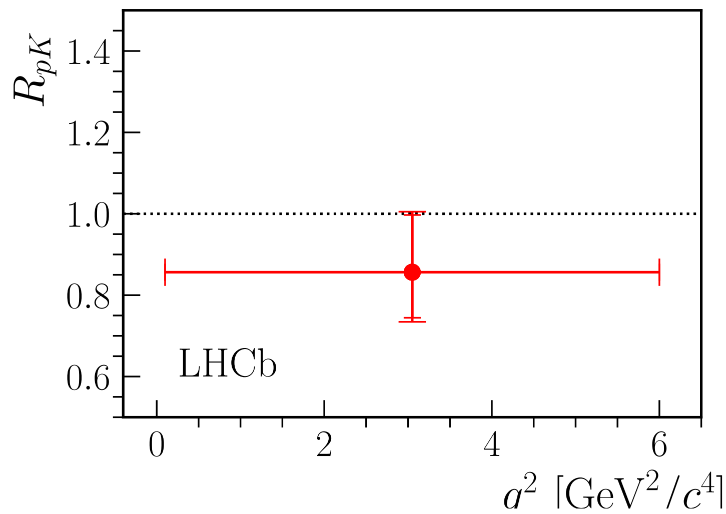
- JHEP 08 (2017) 055
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

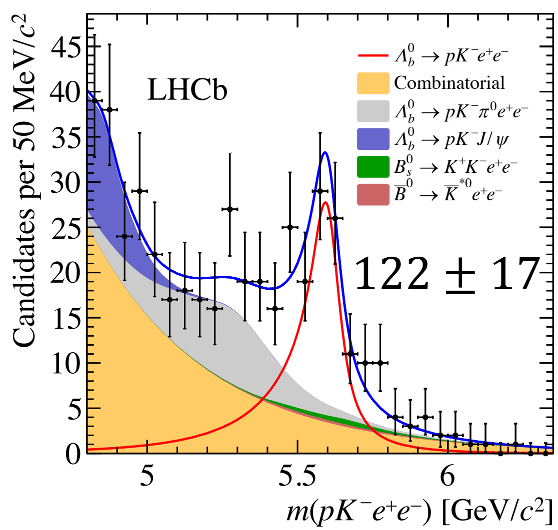
R(pK), results with Run-I+2016

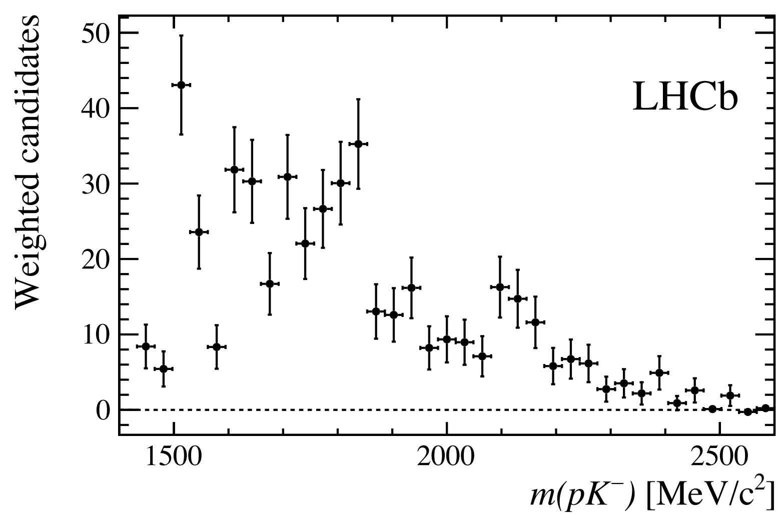
- Compatible with 1, difficult to predict R(pK)?

[JHEP 05 (2020) 040]





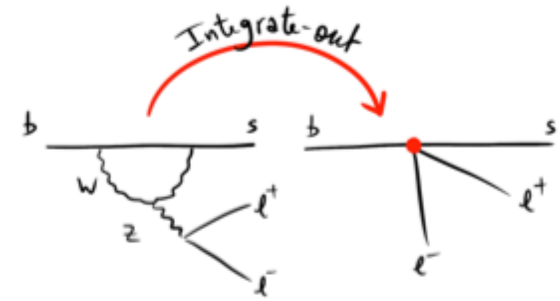




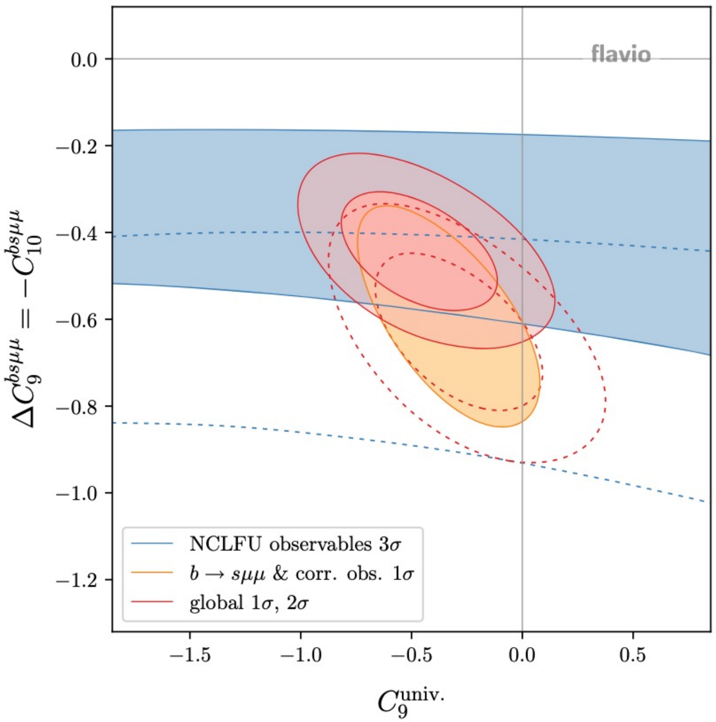
Global fit

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

[J. Aebischer, *et al.*, EPJC 80 (2020) 252]



Coeff.	Best fit	1σ	2σ	Pull
$C_9^{bs\mu\mu}$	-0.97	$[-1.12, -0.81]$	$[-1.27, -0.65]$	5.9σ
$C_9^{\prime bs\mu\mu}$	$+0.14$	$[-0.03, +0.32]$	$[-0.20, +0.51]$	0.8σ
$C_{10}^{bs\mu\mu}$	$+0.75$	$[+0.62, +0.89]$	$[+0.48, +1.03]$	5.7σ
$C_{10}^{\prime bs\mu\mu}$	-0.24	$[-0.36, -0.12]$	$[-0.49, +0.00]$	2.0σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.20$	$[+0.06, +0.36]$	$[-0.09, +0.52]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	-0.53	$[-0.61, -0.45]$	$[-0.69, -0.37]$	6.6σ
C_9^{bsee}	$+0.93$	$[+0.66, +1.17]$	$[+0.40, +1.42]$	3.5σ
$C_9^{\prime bsee}$	$+0.39$	$[+0.05, +0.65]$	$[-0.27, +0.95]$	1.2σ
C_{10}^{bsee}	-0.83	$[-1.05, -0.60]$	$[-1.28, -0.37]$	3.6σ
$C_{10}^{\prime bsee}$	-0.27	$[-0.57, -0.02]$	$[-0.84, +0.26]$	1.1σ
$C_9^{bsee} = C_{10}^{bsee}$	-1.49	$[-1.79, -1.18]$	$[-2.05, -0.79]$	3.2σ
$C_9^{bsee} = -C_{10}^{bsee}$	$+0.47$	$[+0.33, +0.59]$	$[+0.20, +0.73]$	3.5σ
$\left(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}\right) \times \text{GeV}$	-0.006	$[-0.009, -0.003]$	$[-0.014, -0.001]$	2.8σ
$\left(C_S^{\prime bs\mu\mu} = C_P^{\prime bs\mu\mu}\right) \times \text{GeV}$	-0.006	$[-0.009, -0.003]$	$[-0.014, -0.001]$	2.8σ



LU deviations are consistent with $b \to s\mu\mu$ BR and angular analyses if NP only in muon

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
$R_K(1 < q^2 < 6\ \mathrm{GeV})$	0.1	0.025	0.036	0.007	
$R_{K^*}(1 < q^2 < 6\ \mathrm{GeV})$	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

- 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!