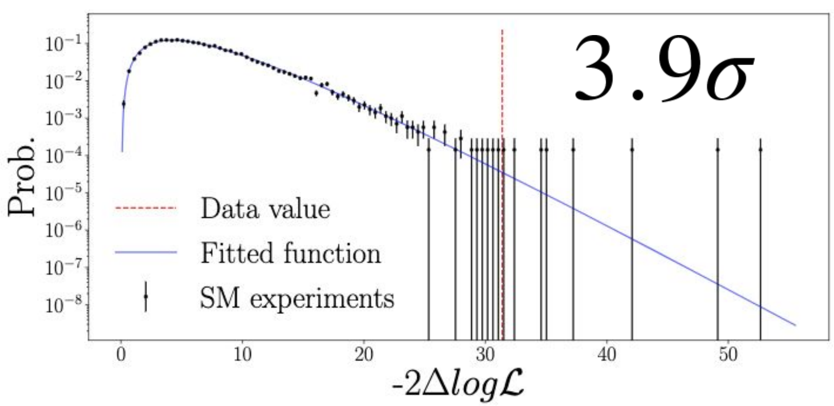
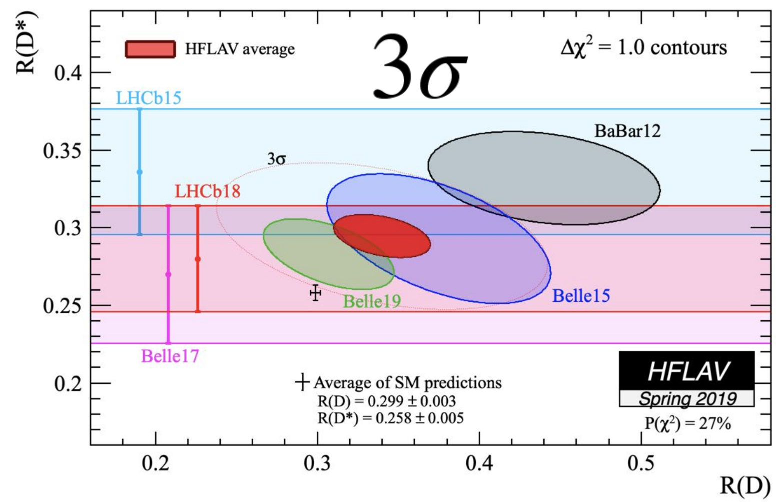
Recent Exciting Results from LHCb

Nico Serra - University of Zurich

$$b \to s \ell \ell$$

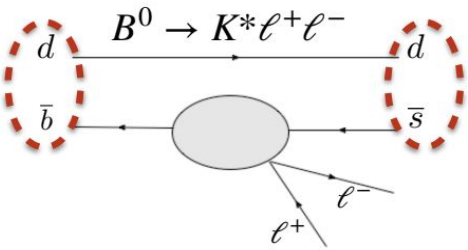


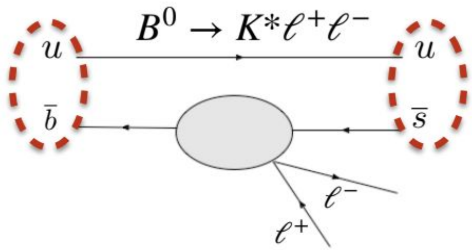
$$b \to c \ell \nu$$

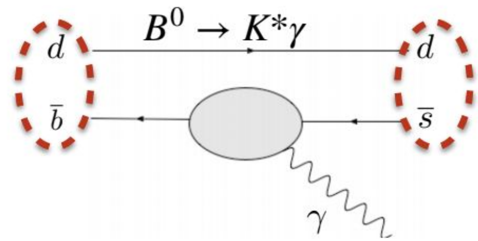


- Rare decays anomalies (LHCb)
- Semileptonic anomalies (LHCb + BaBar/Belle)

Effective Lagrangian - b→sll







$$\Delta\mathcal{L}_{\rm NP}^{b\to s\ell\ell} = \frac{4G_F}{\sqrt{2}}\sum_i C_i \mathcal{O}_i$$

Operators
Long distance ($\mathcal{O}_i$)

Wilson Coefficient
Short distance (C_i)

NP can modify WC or contribute with new operators

$$\mathcal{O}_9^{(\prime)} \propto \left(\bar{s}\gamma_\mu P_{R(L)} b\right)\left(\bar{\ell}\gamma^\mu \ell\right) \qquad \mathcal{O}_S^{(\prime)} \propto \left(\bar{s} P_{R(L)} b\right)\left(\bar{\ell}\gamma^\mu \ell\right)$$

$$\mathcal{O}_7^{(\prime)} \propto \left(\bar{s}\sigma_{\mu\nu} P_{R(L)} b\right) F_{\mu\nu} \qquad \mathcal{O}_{10}^{(\prime)} \propto \left(\bar{s}\gamma_\mu P_{R(L)} b\right)\left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right) \qquad \mathcal{O}_P^{(\prime)} \propto \left(\bar{s} P_{R(L)} b\right)\left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right)$$

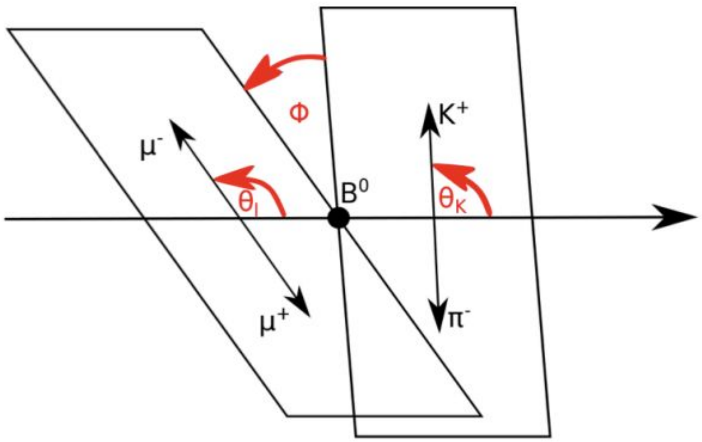
$B \to K^*\gamma$

$B^+ \to K^+\ell\ell$

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

$B \to K^*\ell\ell$

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

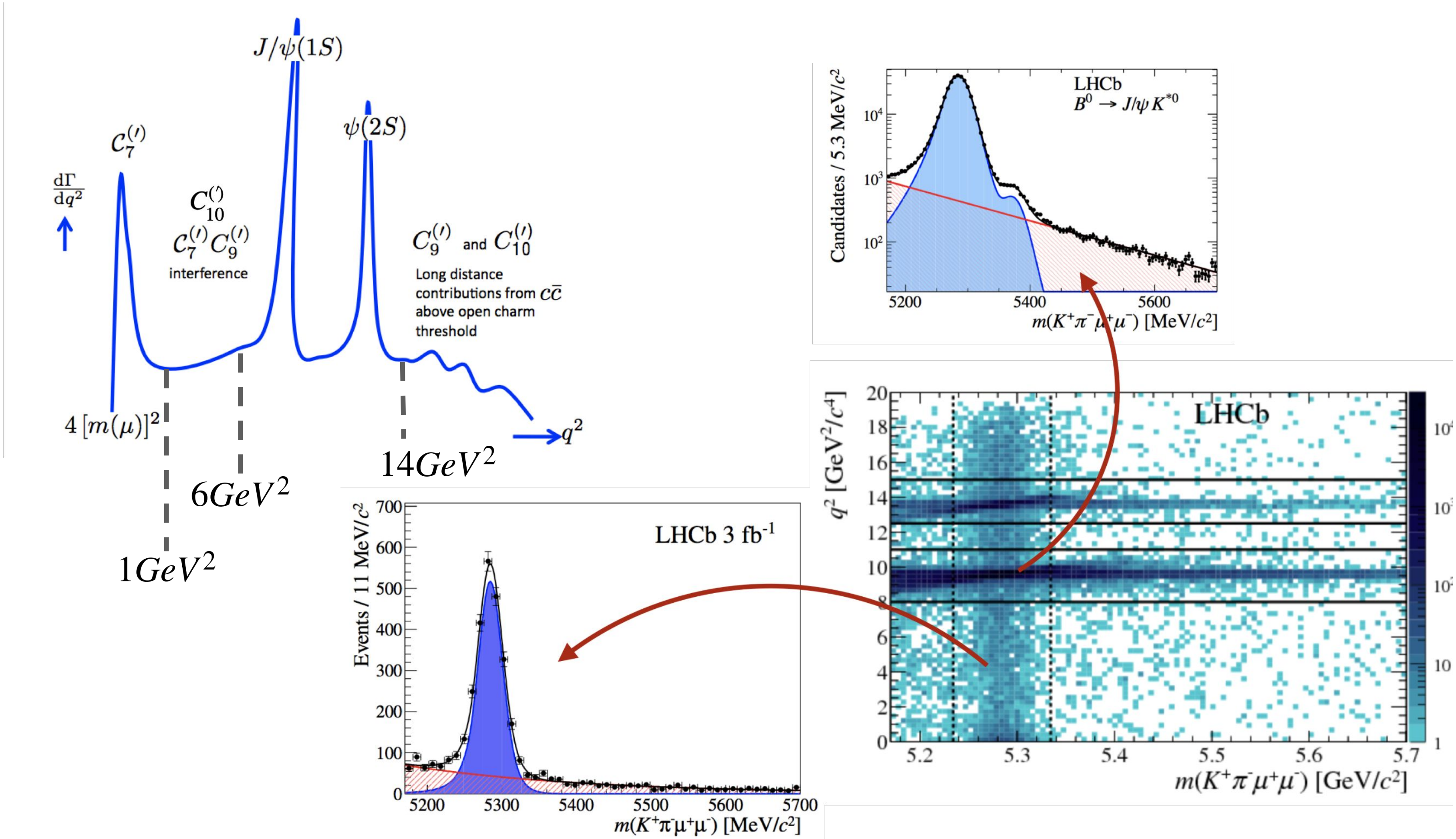


This decay is described by 3 angles (**θ_l ,θ_K ,ϕ**) and the di-muon invariant mass squared (q^2)

This is analogous to the orbitals in atoms, i.e. the spectroscopy allows you to infer about atomic potential

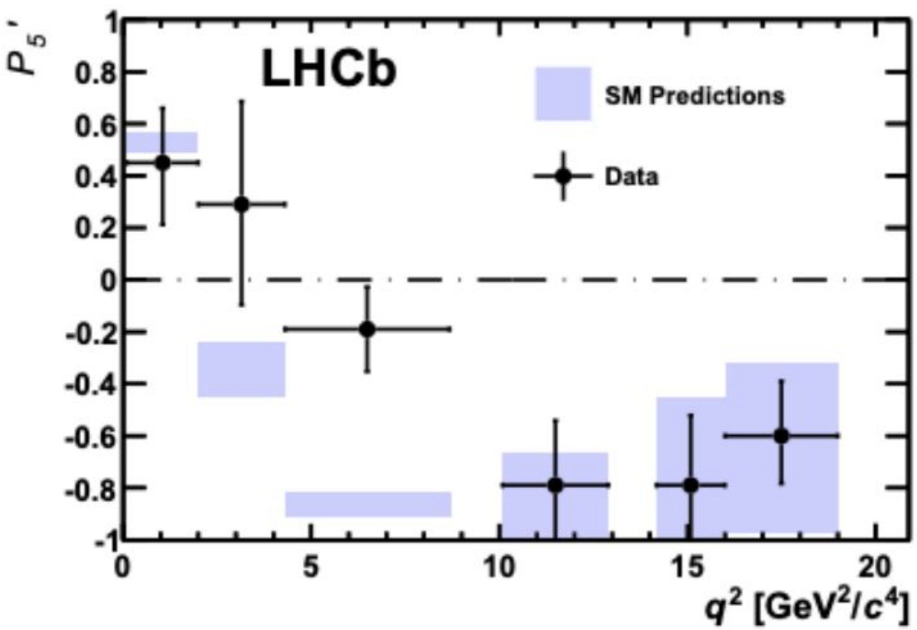
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

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

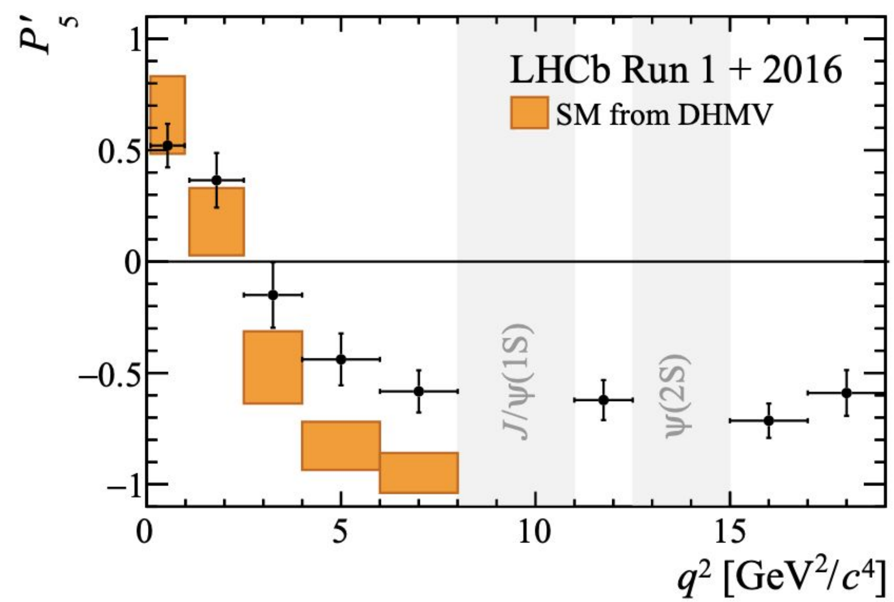

$\frac{d\Gamma}{dq^2}$
$C_7^{(\prime)}$
$J/\psi(1S)$
$\psi(2S)$
$C_{10}^{(\prime)}$
$C_7^{(\prime)} C_9^{(\prime)}$
interference
$C_9^{(\prime)}$ and $C_{10}^{(\prime)}$
Long distance contributions from $c\bar{c}$ above open charm threshold
$4\,[m(\mu)]^2$
q^2
$1GeV^2$
$6GeV^2$
$14GeV^2$
LHCb
$B^0 \to J/\psi K^{*0}$
Candidates / 5.3 MeV/c^2
$m(K^+\pi^-\mu^+\mu^-)$ [MeV/c^2]
LHCb
q^2 [GeV^2/c^4]
$m(K^+\pi^-\mu^+\mu^-)$ [GeV/c^2]
LHCb 3 fb^{-1}
Events / 11 MeV/c^2
$m(K^+\pi^-\mu^+\mu^-)$ [MeV/c^2]

$B \to K^* \mu^+ \mu^-$

Phys. Rev. Lett. 111, 191801 (2013)

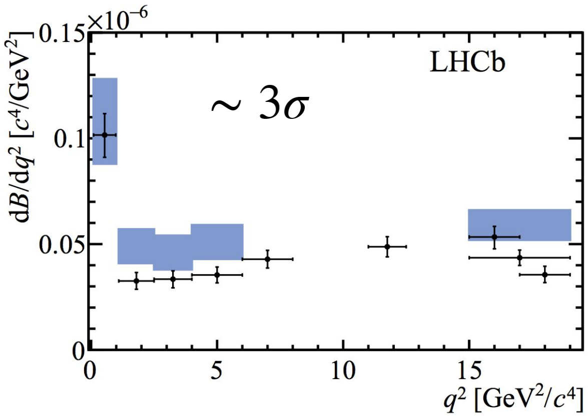


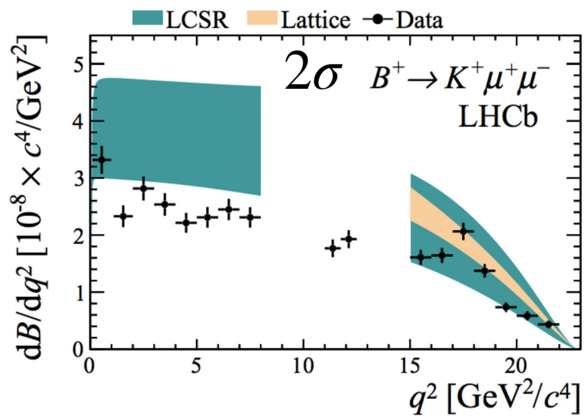
Phys. Rev. Lett. 125, 011802 (2020)

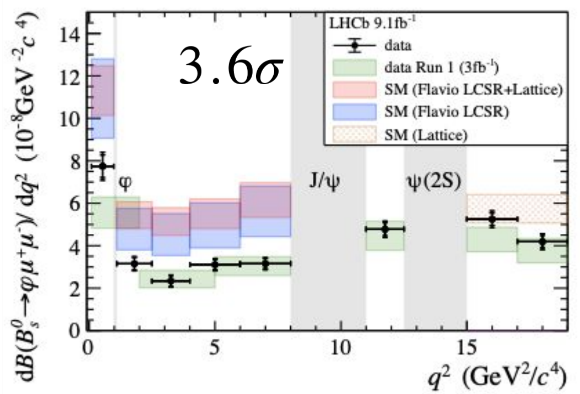


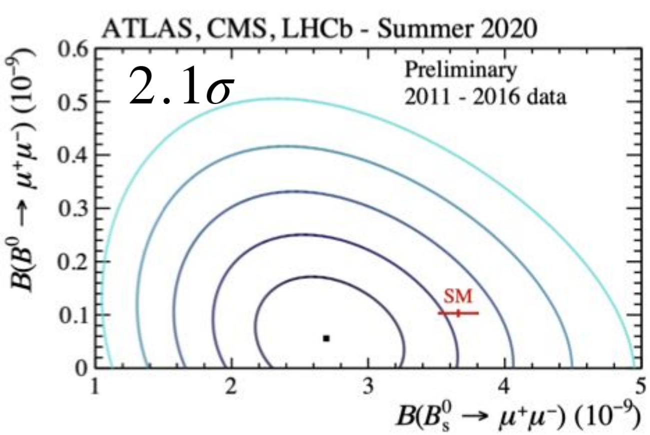
- Discrepancy in P_5' first observed in 2013 with 1fb^{-1}
- Discrepancy confirmed in 2016 (3fb-1) and 2020 (5fb^{-1})
- And in $B^+ \to K^{*+}\mu\mu$ with 9fb^{-1}

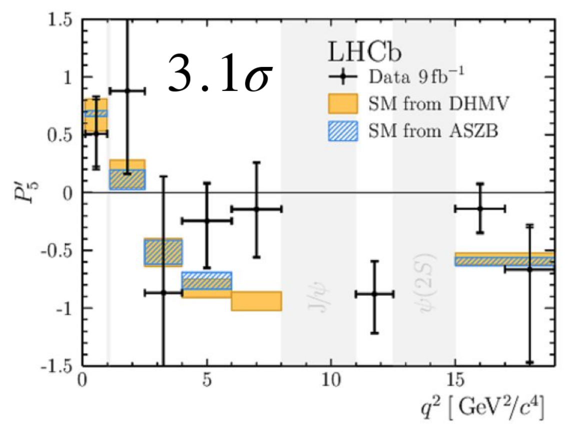
Other b→sμμ anomalies



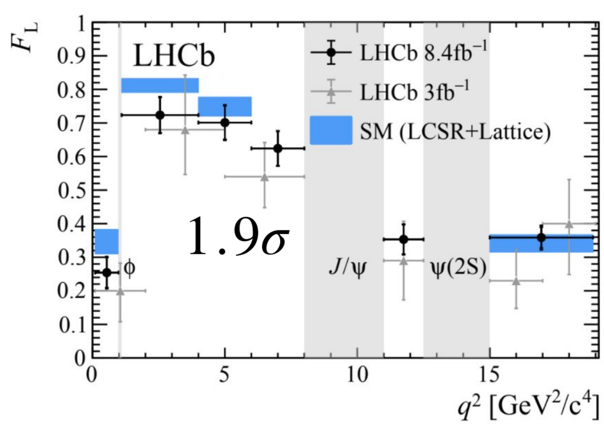






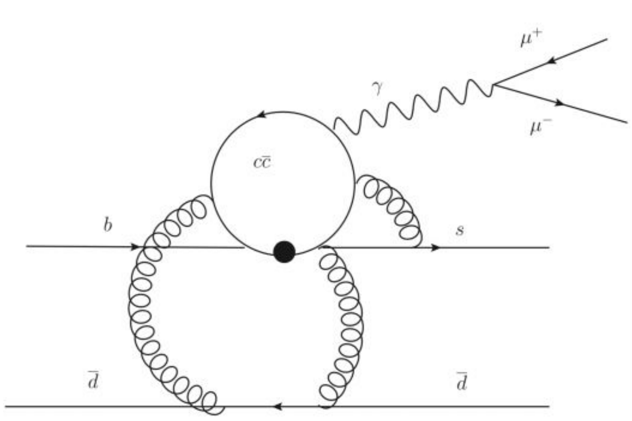


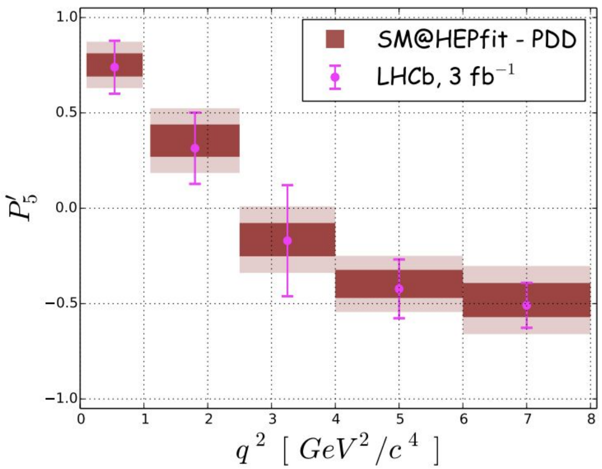
NEW (FPCP2021)!

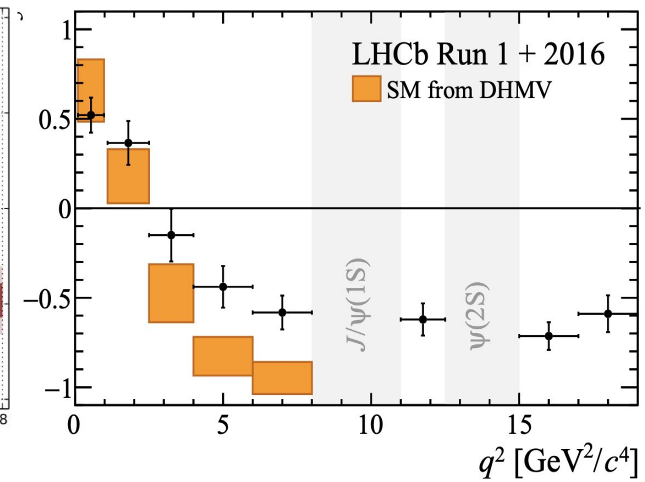


The problem with C_9

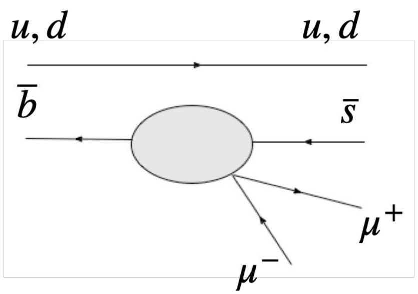
- b→sμμ discrepancies can be explained with the same shift in $C_{9/10}$ simultaneously
- Charm loop affects C_9 and is difficult to compute theoretically
- Long debate in the community https://arxiv.org/abs/1406.0566, https://arxiv.org/abs/1512.07157, https://arxiv.org/abs/1910.12924, https://arxiv.org/abs/1503.03328
- Ongoing attempts to disentangle measure charm loop from data https://arxiv.org/abs/1805.06378, http://arxiv.org/abs/1709.03921, https://arxiv.org/abs/2011.09813, https://arxiv.org/abs/2011.12856

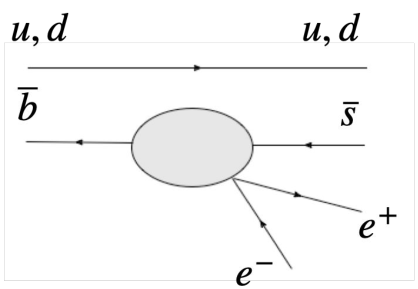






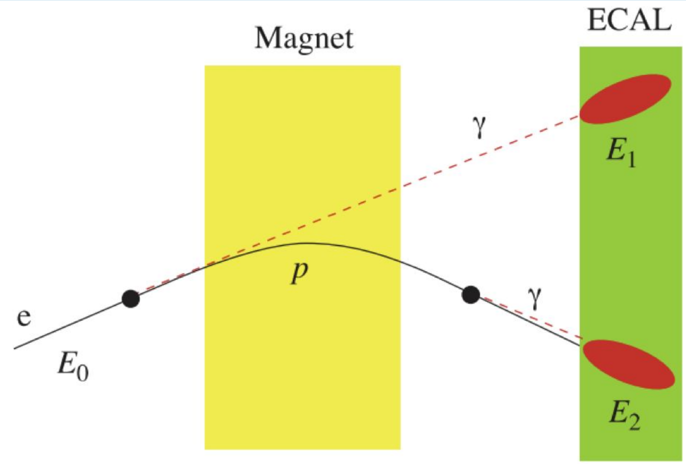
Testing Lepton Universality

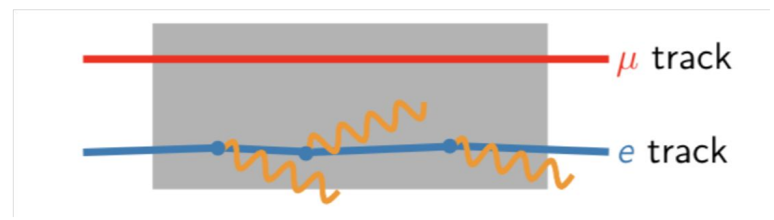




EPJC 76 (2016) 8, 440

$= 1.00 \pm 0.01$

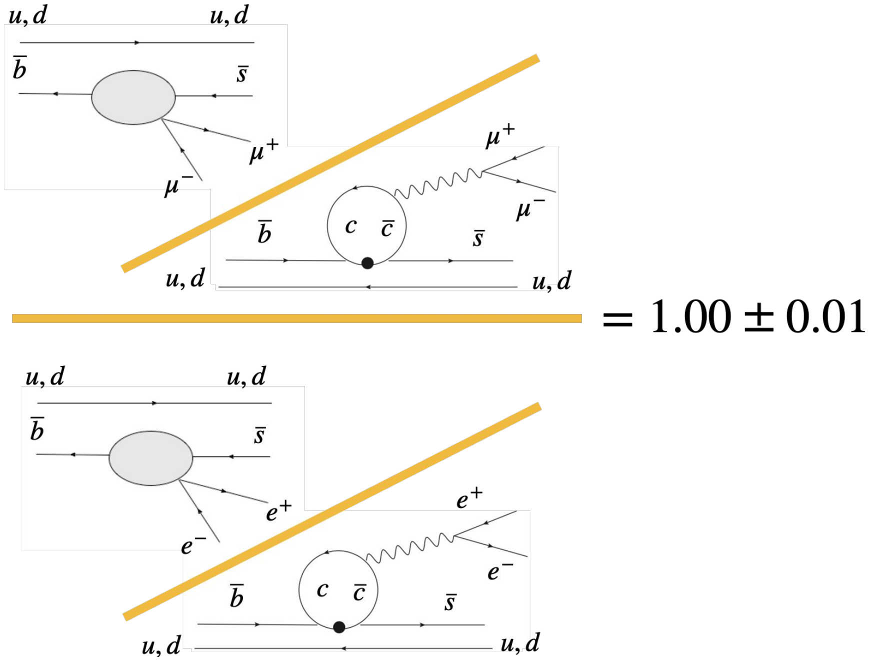


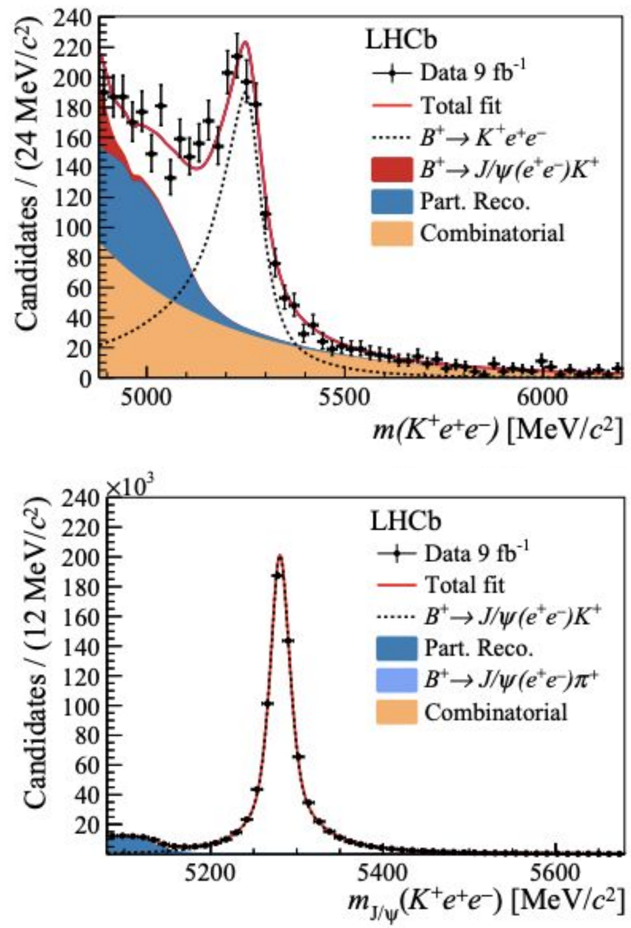


Electron emit bremsstrahlung photons spoiling q^2, inv mass and momentum resolutions:

- More complicated and difficult J/ψ veto
- Harder trigger, reconstruction, PID, smaller efficiency wrt muons

Testing LFU with a double ratio



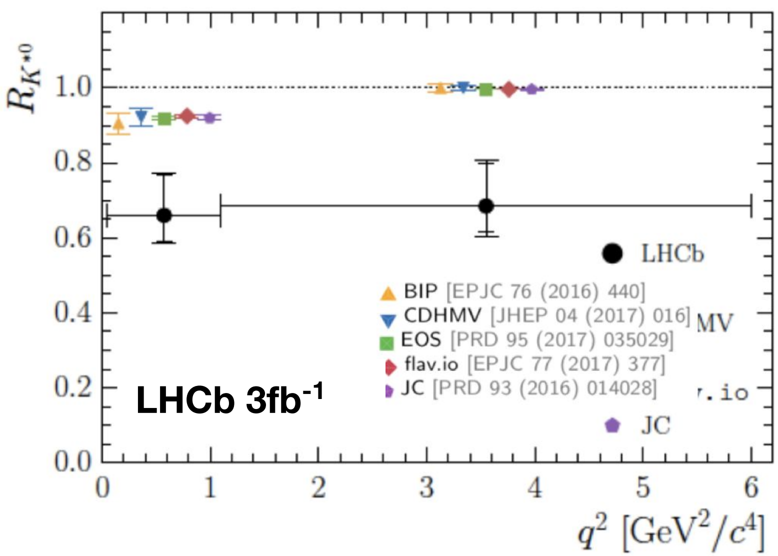


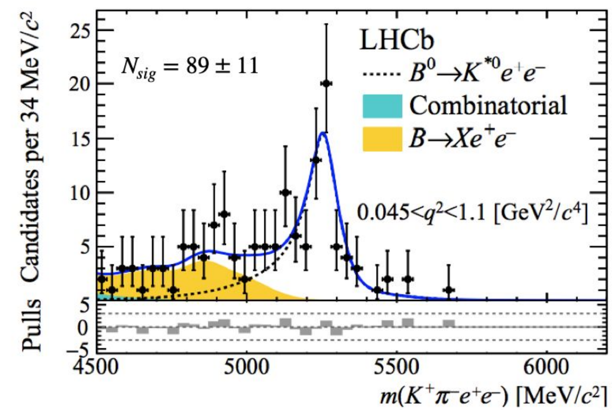
- Double ratio very stable against efficiency mismodeling
- Systematics cancel out at first order in the double ratio
- Decays $B^{+,0} \to J/\psi\ K^{+,*}$ and $B^{+,0} \to \psi(2S)\ K^{+,*}$ great control channels

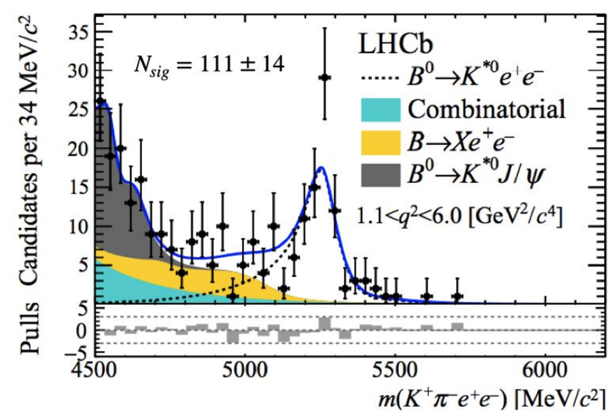
Other b →sll LFU tests at LHCb

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

LHCb Coll. JHEP 1708 (2017) 055





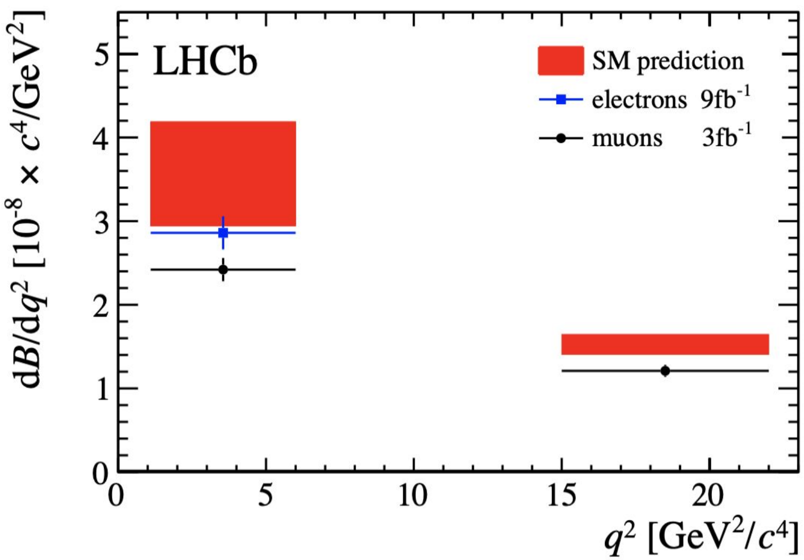


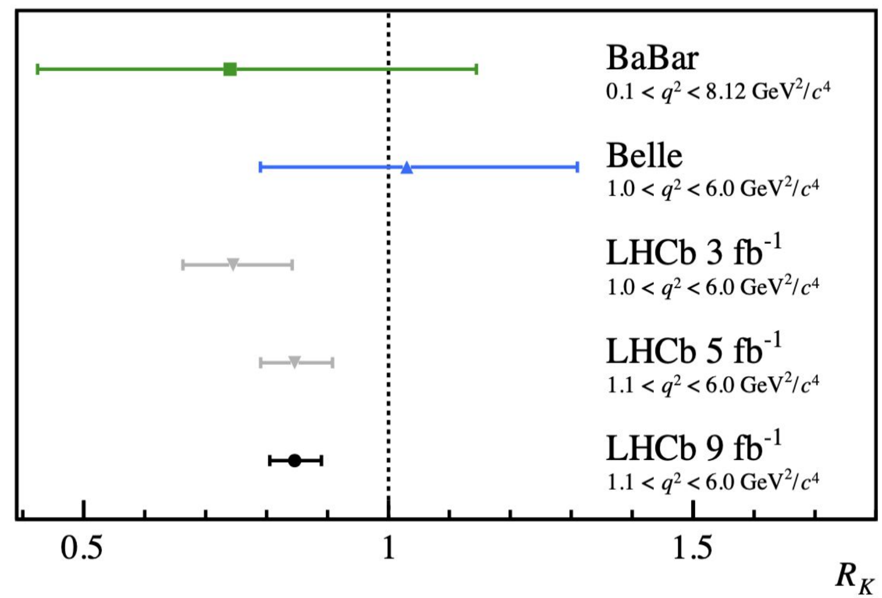
$$R_{K^{*0}} = \begin{cases} 0.66\,^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2c^4 \\ 0.69\,^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\ \text{GeV}^2c^4 \end{cases}$$

First evidence of violation to LFUV

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

https://arxiv.org/abs/2103.11769





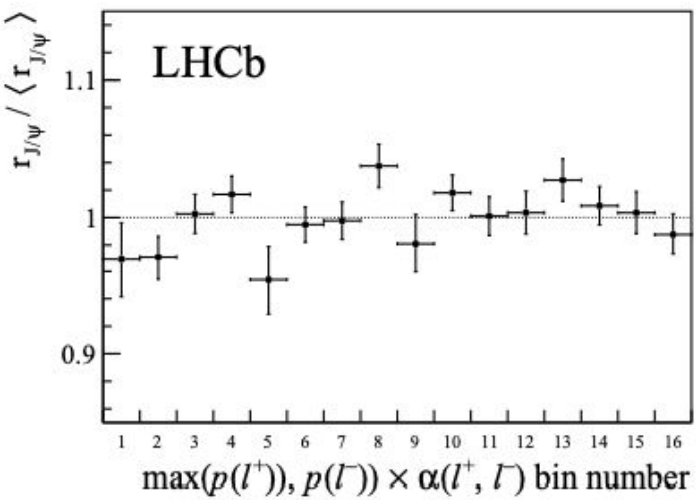
$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

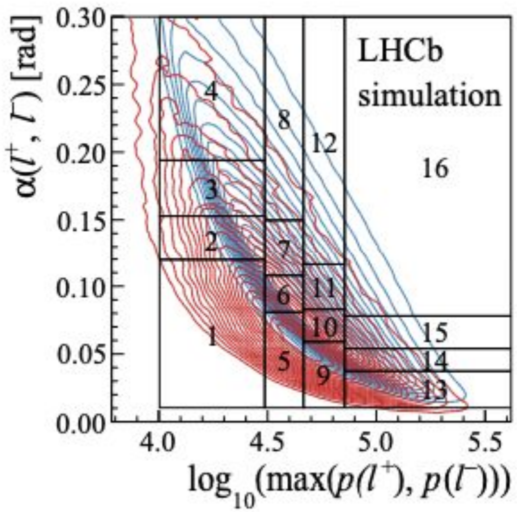
Deviation of 3.1σ with respect to SM, i.e. first evidence for LFU violation in this decay

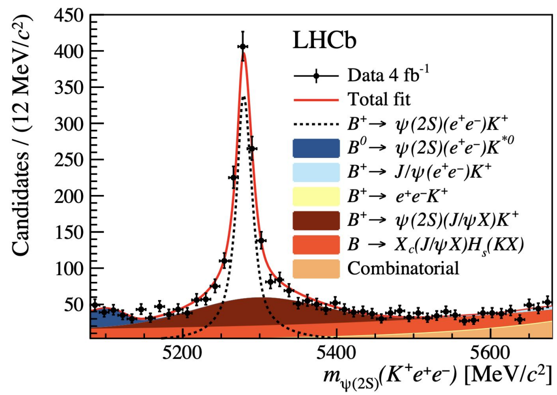
Measuring $r_{J/\psi}$

$$r_{J/\psi} = \frac{\mathfrak{B}(B^+ \to J/\psi(\to \mu\mu) K^+)}{\mathfrak{B}(B^+ \to J/\psi(\to ee) K^+)}$$

Measuring the single ratio $r_{J/\psi}$ is one of the main cross check $r_{J/\psi} = 0.981 \pm 0.020$







$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 0.997 \pm 0.011$$

Theory fits

Matias et al https://arxiv.org/pdf/2104.08921.pdf

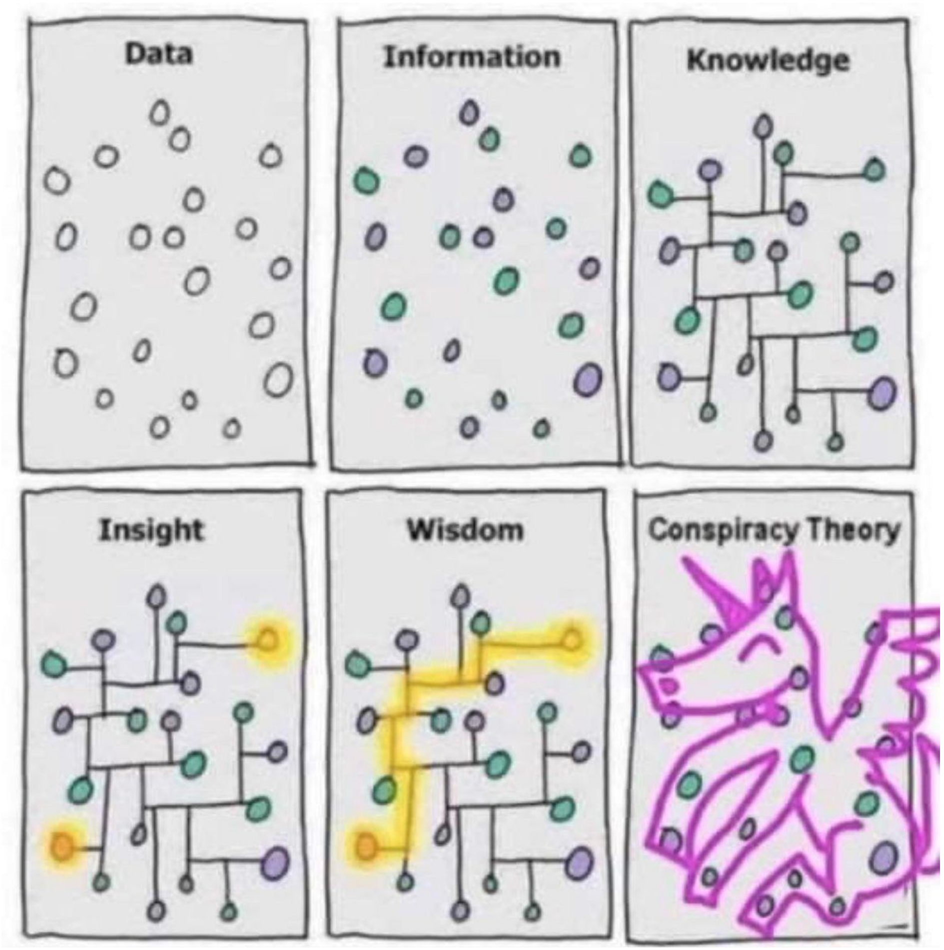
Scenario		$\mathrm{Pull}_{\mathrm{SM}}$	p-value
Scenario 5	$\mathcal{C}_{9\mu}^{\mathrm{V}}$ $\mathcal{C}_{10\mu}^{\mathrm{V}}$ $\mathcal{C}_{9}^{\mathrm{U}} = \mathcal{C}_{10}^{\mathrm{U}}$	6.6	38.6 %
Scenario 6	$\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$ $\mathcal{C}_{9}^{\mathrm{U}} = \mathcal{C}_{10}^{\mathrm{U}}$	6.8	40.1 %
Scenario 7	$\mathcal{C}_{9\mu}^{\mathrm{V}}$ $\mathcal{C}_{9}^{\mathrm{U}}$	6.9	41.7 %
Scenario 8	$\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$ $\mathcal{C}_{9}^{\mathrm{U}}$	7.3	53.8 %

Altmannshofer et al. https://arxiv.org/pdf/2103.13370.pdf

	$b \to s\mu\mu$		LFU, $B_s \to \mu\mu$		all rare B decays	
Wilson coefficient	best fit	pull	best fit	pull	best fit	pull
$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9^{\prime bs\mu\mu}$	$+0.39^{+0.27}_{-0.26}$	1.5σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.14^{+0.13}_{-0.13}$	1.0σ
$C_{10}^{\prime bs\mu\mu}$	$-0.10^{+0.17}_{-0.16}$	0.6σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.04^{+0.10}_{-0.10}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.34^{+0.16}_{-0.16}$	2.1σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$-0.01^{+0.12}_{-0.12}$	0.1σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

- Even Silvestrini et al. (https://arxiv.org/abs/2011.01212) find 6σ of NP when fitting with their framework
- Fit with “clean” observables around 4.7σ (https://inspirehep.net/literature/1853015, https://arxiv.org/abs/2103.12738)

What about the Look-Elsewhere Effect?

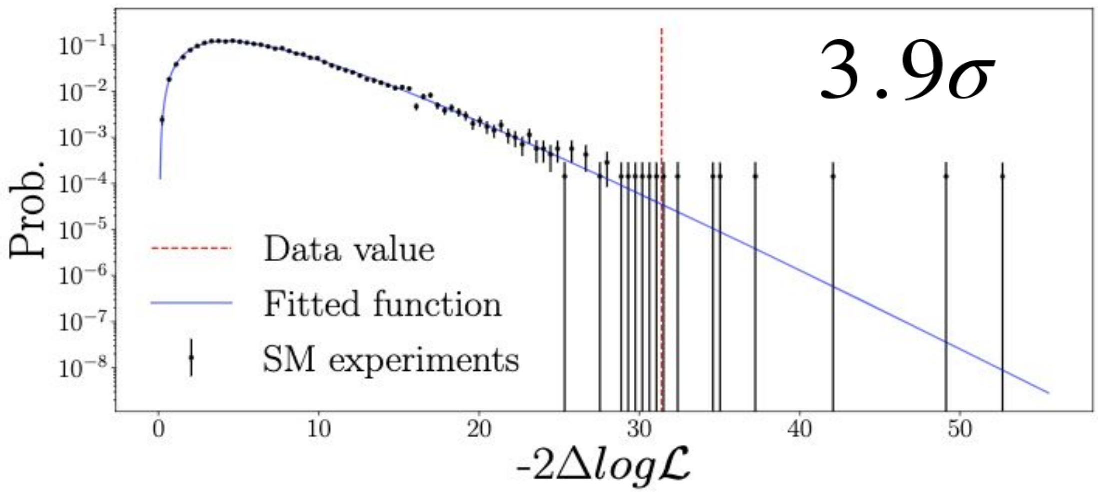


Credit Stephan Grabmeier

University of Zurich[UZH]

LEE in b→sll and hyper-conservative approach

- Calculate the significance using the most conservative theory approach and taking into account the Look-elsewhere effect in b→ sll

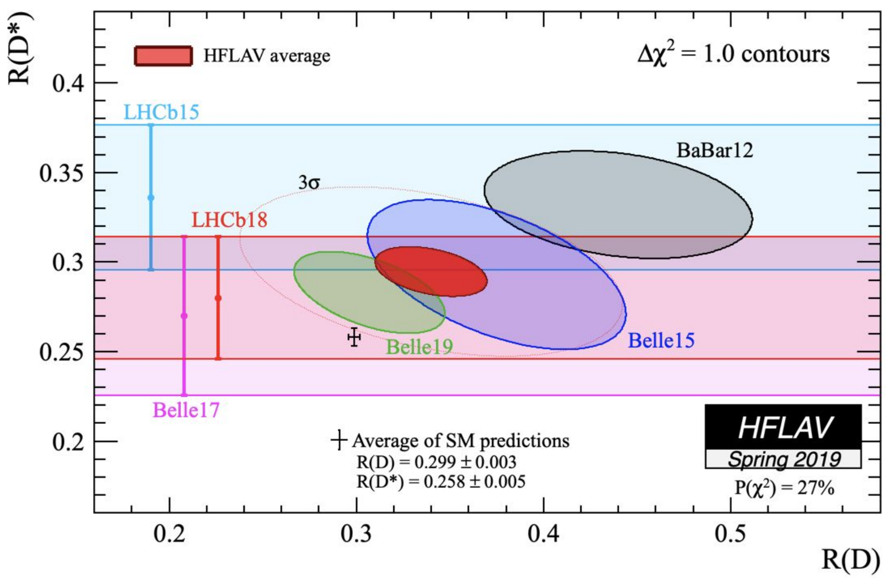


D. Lancierini, G. Isidori, P. Owen, NS

https://arxiv.org/abs/2104.05631

- Use the most general based of Operators
- Generate pseudo-experiments based on SM
- Consider the WC C_9 as a nuissance parameter of the SM
- Calculate the DLL and compare with that obtained in data

Combination of b⟶clν anomalies



$$R\left(D^{(*)}\right) = \frac{B \to D^{(*)}\tau\nu}{B \to D^{(*)}\mu\nu} = \frac{signal}{normalization}$$

$\tau \to \mu 2\nu$

LHCb Coll., Phys.Rev.Lett. 115 (2015) no.11, 111803

$$R(D^*)_{\tau\to\mu 2\nu} = 0.336 \pm 0.027 \pm 0.030$$

$\tau \to 3\pi\nu$

LHCb Coll., Phys. Rev. D 97, 072013 (2018)

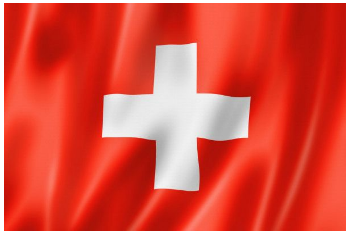
$$R(D^*)_{\tau\to 3\pi\nu} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

- Combined tension in R(D) and R(D*) is about 3σ

Swiss contribution

Some of the main measurements on the anomalies are done by CH groups:

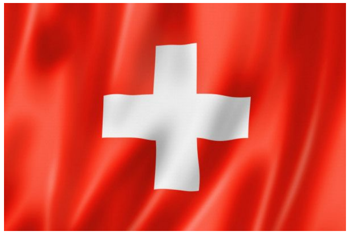
- Measurements of angular observables (including the first) of $B \to K^*\mu\mu$ -- UZH
- Recent R_K measurement -- UZH



Ongoing measurements:

- New standard candle $D_{(s)} \to \phi(\to ll)\pi$ -- UZH
- LFU asymmetries in angular observables -- UZH
- World's first measurement of $R_{K\pi\pi}$ -- EPFL, UZH
- Simultaneous measurement of R_K and $R_K{}^*$ -- EPFL, UZH
- LF-Difference in WC in $B \to K^*ll$ -- UZH, EPFL
- World's first measurement of $R_{K\pi}$ -- UZH
- Measurement of new semileptonic LFU ratios $R(D^+)$ and $R(L_c)$ -- UZH
- Measurements of WC in semileptonic decays -- UZH
- Search for $B^+ \to K^+\tau\tau$ using the dimuon distribution of $B^+ \to K^+\mu\mu$ decay -- UZH
- Amplitude analysis of $B^* \to K^*\mu\mu$ decay -- UZH
- Measurement of R_K at high-q^2 -- UZH

Swiss contribution

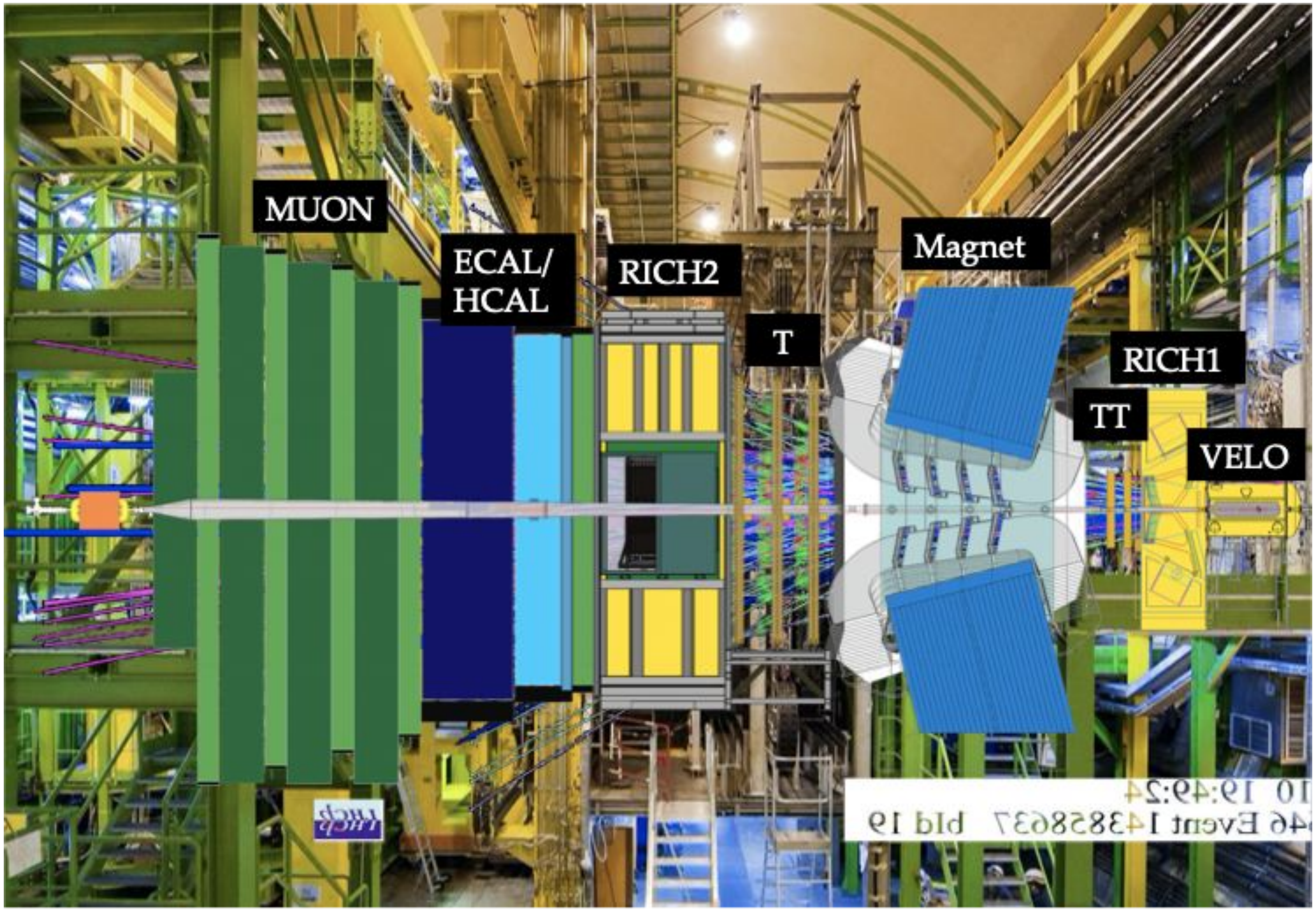


- Strong CH theory community working on the anomalies:
  - Gino Isidori -- UZH
  - Admir Greljo -- BERN
  - Andreas Crivellin -- PSI, UZH

- The collaboration between experimentalists and theorists has been crucial to propose new methods, see for instance:
  - https://arxiv.org/abs/1909.04608
  - https://arxiv.org/abs/2001.04470
  - https://arxiv.org/abs/2104.0563
  - https://arxiv.org/abs/1503.04100
  - https://arxiv.org/abs/1610.08761
  - https://arxiv.org/abs/1805.06378
  - https://arxiv.org/abs/1805.06401

Thanks for the attention and stay tuned!

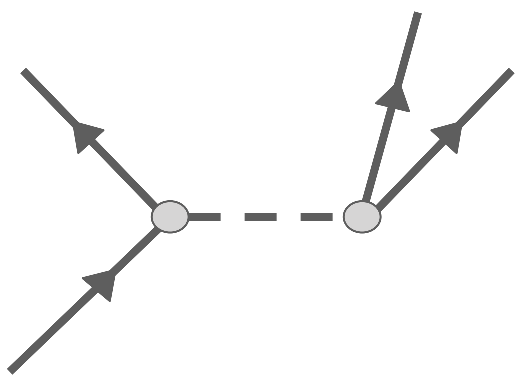
LHCb Experiment



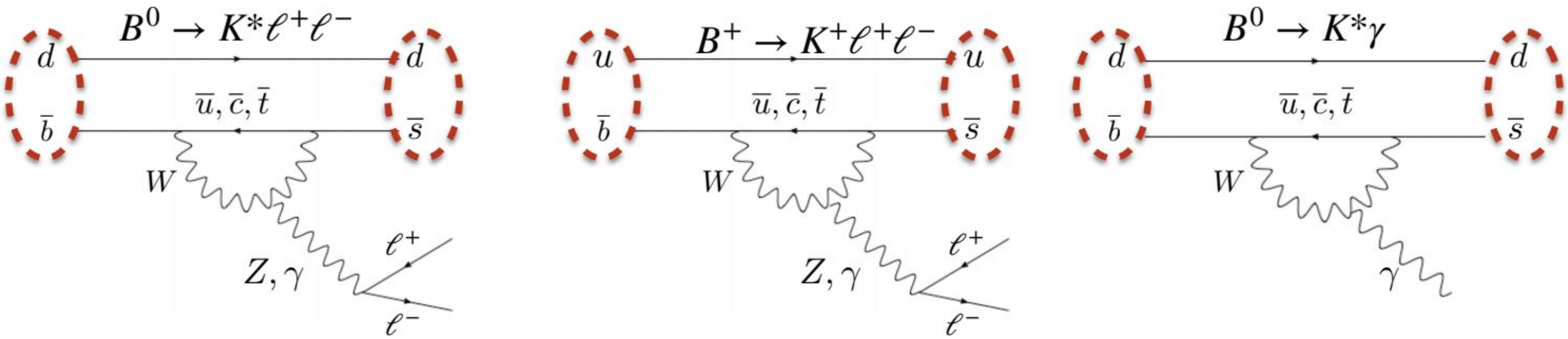
Operator Product Expansion

$$|M_{i,f}|^2 = \langle \psi_{\text{Daughter}} \phi_\beta \psi_\nu | \hat{H}_{\text{int}} | \psi_{\text{Parent}} \rangle$$

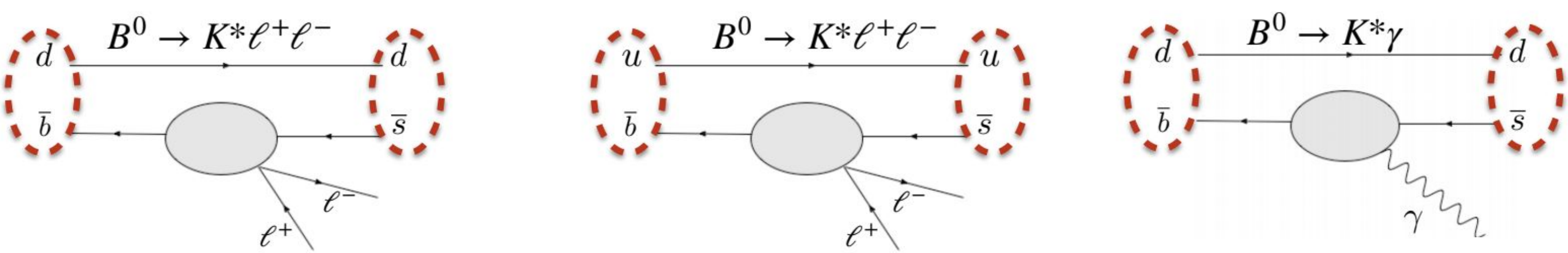
$$\hat{H}_{\text{int}} = \begin{cases} G_V \hat{1} \hat{\tau} & \text{Fermi decay} \\ G_A \hat{\sigma} \hat{\tau} & \text{Gamow–Teller Decay} \end{cases}$$



$b \rightarrow s\ell\ell$



Use an effective operator approach, similar to Fermi theory of weak interaction

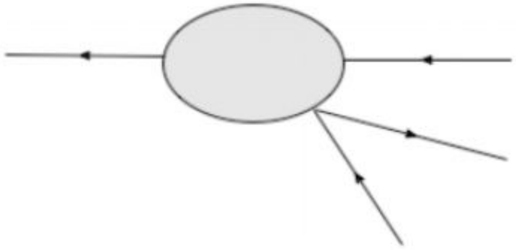


$$\Delta\mathcal{L}_{\text{NP}}^{b\rightarrow s\ell\ell} = \frac{4G_F}{\sqrt{2}} \sum_i C_i \mathcal{O}_i$$

Theory description of our system

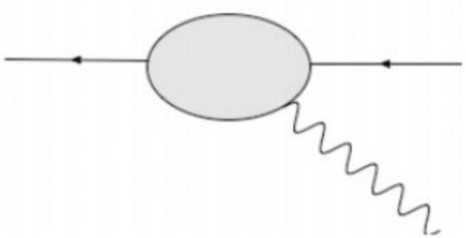
Most general basis entering the b → sll

$$\mathcal{O}_9^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}_{10}^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$
$$\mathcal{O}_9^{\ell\prime} = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}_{10}^{\ell\prime} = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$
$$\mathcal{O}_{\hat{S}}^\ell = (\bar{s}_L b_R)(\bar{\ell}_R\ell_L)\,, \qquad \mathcal{O}_{\hat{S}}^{\ell\prime} = (\bar{s}_R b_L)(\bar{\ell}_L\ell_R)\,.$$



Considering also b → sγ transitions

$$\mathcal{O}_7^{(\prime)} = \bar{s}\left(1 \pm \gamma_5\right)\sigma_{\mu\nu} b\, F^{\mu\nu}$$



The $O_7^{(\prime)}$ operators are strongly constrained by LHCb

Amplitude K*mm

- The decay is described by six complex amplitudes $A^{L,R}_{0,\|,\perp}$
- Correspond to different transversity state of the K^*
- and different (left- and right-handed) chiralities of the dimuon system

$$
\begin{aligned}
F_L &= \frac{A_0^2}{A_\|^2 + A_\perp^2 + A_0^2} = 1 - F_T \\
S_3 &= \frac{1}{2}\frac{A_\perp^{L2} - A_\|^{L2}}{A_\|^2 + A_\perp^2 + A_0^2} + L \to R \\
S_4 &= \frac{1}{\sqrt{2}}\frac{\Re(A_0^{L*}A_\|^L)}{A_\|^2 + A_\perp^2 + A_0^2} + L \to R \\
S_5 &= \sqrt{2}\frac{\Re(A_0^{L*}A_\perp^L)}{A_\|^2 + A_\perp^2 + A_0^2} - L \to R \\
A_{FB} &= \frac{8}{3}\frac{\Re(A_\perp^{L*}A_\|^L)}{A_\|^2 + A_\perp^2 + A_0^2} - L \to R \\
S_7 &= \sqrt{2}\frac{\Im(A_0^{L*}A_\|^L)}{A_\|^2 + A_\perp^2 + A_0^2} + L \to R \\
S_8 &= \frac{1}{\sqrt{2}}\frac{\Im(A_0^{L*}A_\perp^L)}{A_\|^2 + A_\perp^2 + A_0^2} + L \to R \\
S_9 &= \frac{\Im(A_\perp^{L*}A_\|^L)}{A_\|^2 + A_\perp^2 + A_0^2} - L \to R
\end{aligned}
$$

$$
\begin{aligned}
A_0^{L,R} &\propto \left[C^+_{9\mp10}A_{12} + C_7^+ T_{23}\right] \\
A_\|^{L,R} &\propto \left[C^-_{9\mp10}A_1 + C_7^- T_2\right] \\
A_\perp^{L,R} &\propto \left[C^-_{9\mp10}V + C_7^- T_1\right]
\end{aligned}
$$

$$
\begin{aligned}
R_1 &= \frac{T_1}{V} \sim 1 \\
R_2 &= \frac{T_2}{A_1} \sim 1 \\
R_3 &= \frac{T_{23}}{A_{12}} \sim \frac{q^2}{m_B^2}
\end{aligned}
$$

$$
\begin{aligned}
A_\perp^{L,R} &= \sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\text{eff}} + \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}'_{10}) + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\text{eff}} + \mathcal{C}_7^{\text{eff}\prime})\right]\xi_\perp(E_{K^*}) \\
A_\|^{L,R} &= -\sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}'_{10}) + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime})\right]\xi_\perp(E_{K^*}) \\
A_0^{L,R} &= -\frac{Nm_B(1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}}\left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}'_{10}) + 2\hat{m}_b(\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime})\right]\xi_\|(E_{K^*})
\end{aligned}
$$

Amplitude K*mm

$$A_0^{L,R} \propto [C^{+}_{9\mp10} A_{12} + C^{+}_7 T_{23}]$$
$$A_{\|}^{L,R} \propto [C^{-}_{9\mp10} A_1 + C^{-}_7 T_2]$$
$$A_{\perp}^{L,R} \propto [C^{-}_{9\mp10} V + C^{-}_7 T_1]$$

$$R_1 = \frac{T_1}{V} \sim 1$$
$$R_2 = \frac{T_2}{A_1} \sim 1$$
$$R_3 = \frac{T_{23}}{A_{12}} \sim \frac{q^2}{m_B^2}$$

$$A_{\perp}^{L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\rm eff} + \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}'_{10}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\rm eff} + \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\perp}(E_{K^*})$$

$$A_{\|}^{L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}'_{10}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\perp}(E_{K^*})$$

$$A_0^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}'_{10}) + 2\hat{m}_b (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_{\|}(E_{K^*})$$

We now build ratios such that the same combination of FF appears in the numerator and in the denominator

$$P'_5 \propto \frac{\Re(A_0 A_{\perp})}{\sqrt{|A_0|^2 \times |A_{\perp}|^2}}$$

Amplitude K*mm

- The number of degrees of freedom are 3x2x2 = 12
- However there are 4 symmetries of the angular distributions, so there are 8 independent observables
- The maximum number of "clean" observables is 6

$$P_1 = A_T^{(2)} = \frac{2S_3}{(1-F_L)} = \frac{A_\perp^{L2} - A_\parallel^{L2}}{A_\parallel^2 + A_\perp^2} + L \to R$$

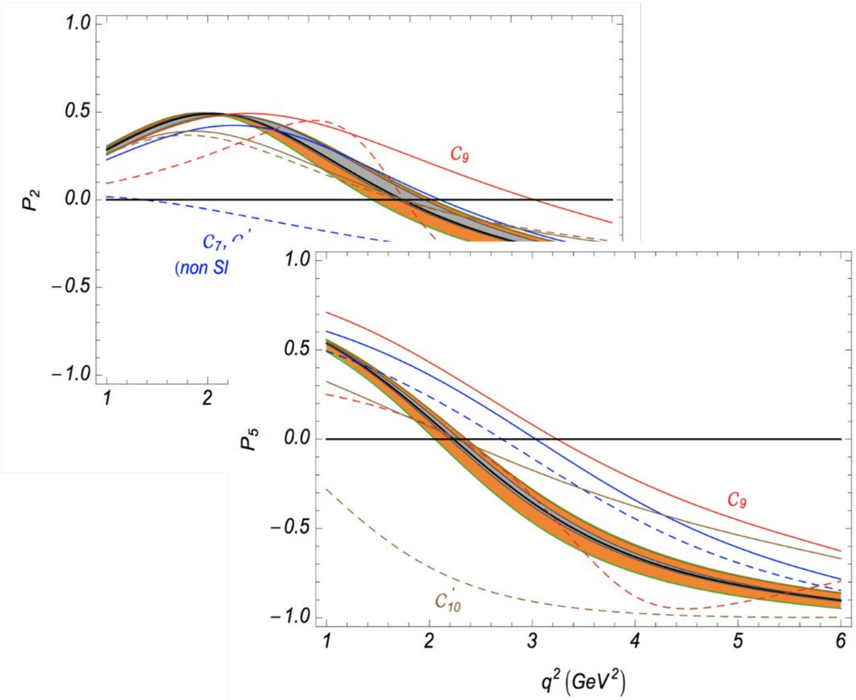
$$P_2 = 2A_T^{Re} = \frac{2A_{FB}}{3(1-F_L)} \propto \frac{\Re(A_\perp^{L*} A_\parallel^L)}{A_\parallel^2 + A_\perp^2} - L \to R$$

$$P_3 = \frac{S_9}{(1-F_L)} = \frac{\Im(A_\perp^{L*} A_\parallel^L)}{A_\parallel^2 + A_\perp^2} - L \to R$$

$$P_4' = \frac{S_4}{\sqrt{F_L(1-F_L)}} \propto \frac{\Re(A_0^{L*} A_\parallel^L)}{\sqrt{|A_0|^2 |A_\parallel|^2}} + L \to R$$

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}} \propto \frac{\Re(A_0^{L*} A_\perp^L)}{\sqrt{|A_\perp|^2 |A_0|^2}} - L \to R$$

$$P_6' = \frac{S_7}{\sqrt{F_L(1-F_L)}} \propto \frac{\Im(A_0^{L*} A_\parallel^L)}{\sqrt{|A_\parallel|^2 |A_0|^2}} + L \to R$$



Charm loop

$$\mathcal{A}_\lambda^{L,R} = N_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

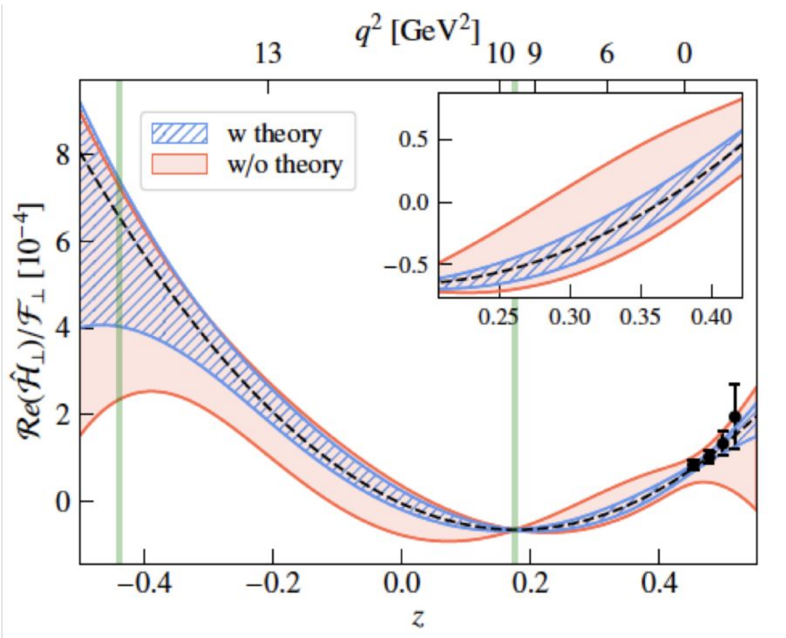
- ✦ Wilson coefficients
- ✦ Form factors
- ✦ Non-local hadronic matrix elements

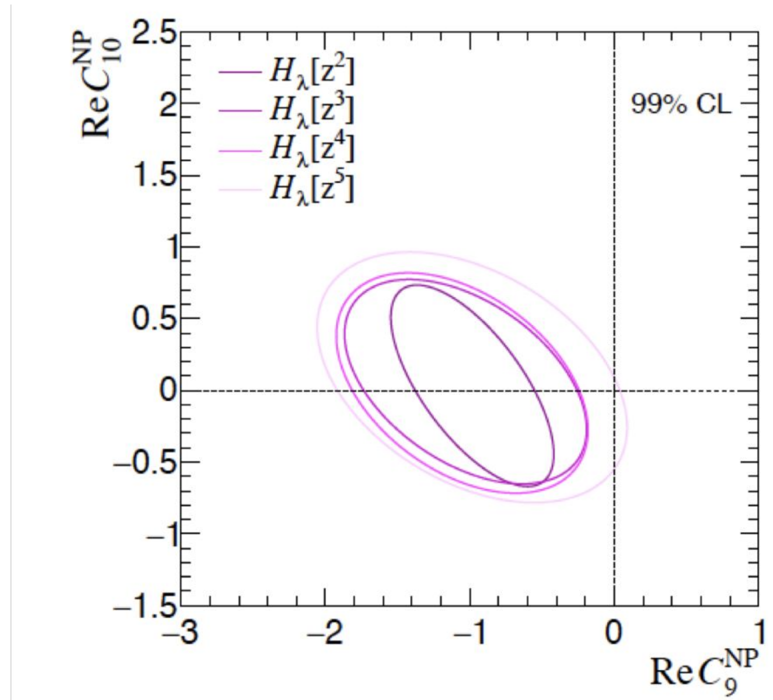
Mapping $q^2 \to z(q^2)$

$$\mathcal{H}_\lambda(z) = \frac{1 - zz^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - zz^*_{\psi(2S)}}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z) \xrightarrow[\text{expansion}]{\text{polynomial}} \hat{\mathcal{H}}_\lambda(z) = \left[\sum_k \alpha_k^{(\lambda)} z^k \right] \mathcal{F}_\lambda(z)$$

- ✳ analytic within $|z| = 1$
- ✳ expansion used up to $z \sim 0.4$
- ✳ cut-off of the series introduce a model bias

Charm Loop

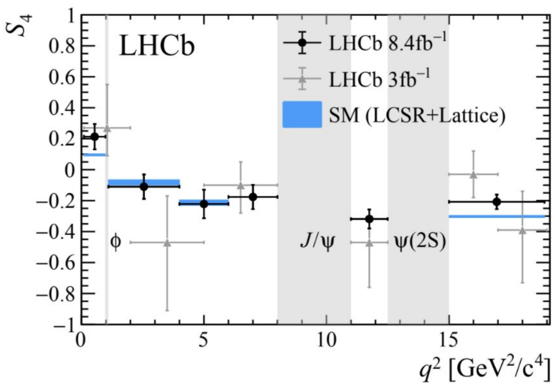


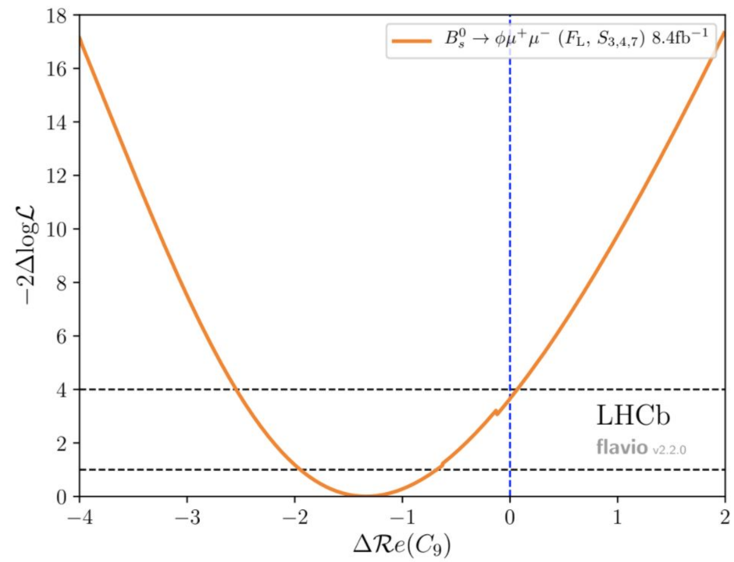


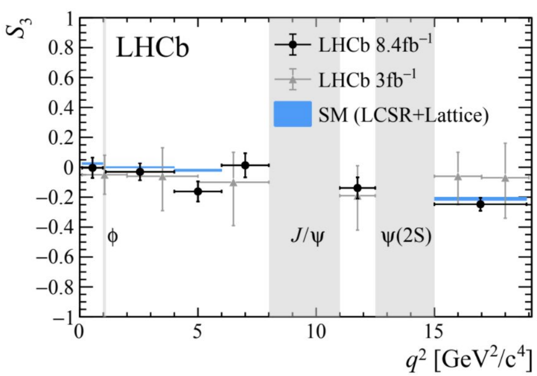
Mauri/Chrzaszcz/NS/vanDyk/Silva arXiv:1805.06378

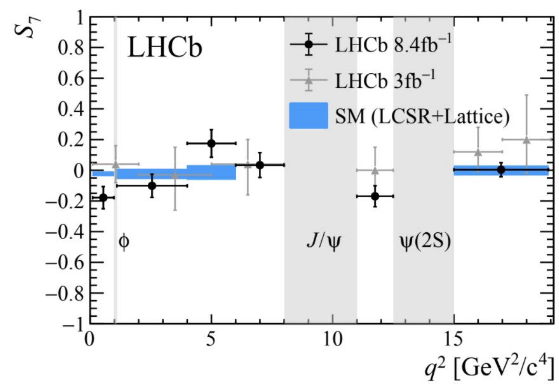
- Extension of the parametrisation of the model in arXiv:1709.03921, including points at negative q^2
- Fit much more stable with the theory points, but not yet a rigorous procedure to evaluate systematics

$B_s \to \phi\mu\mu$ angular analysis









Amplitude analysis B→ K*mm

***classic* angular analysis**

2 steps procedure:

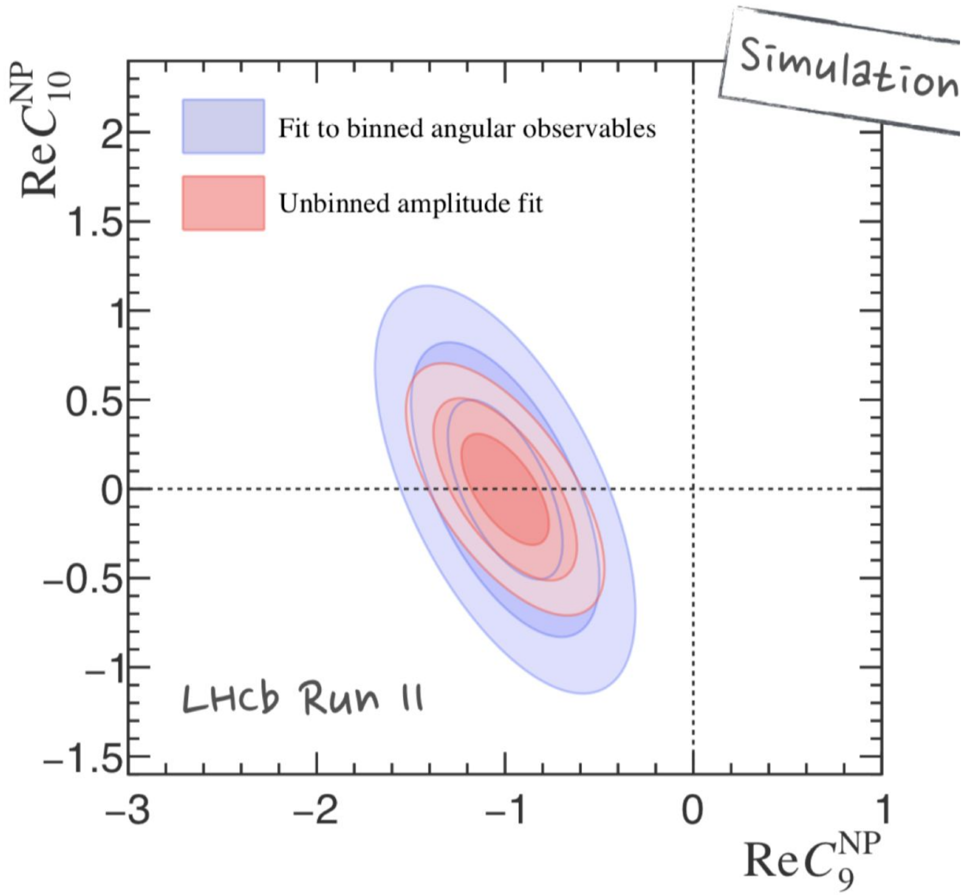
- fit for angular observables S_i
- fit for Wilson coeff. (using same model for charm-loop)

VS

amplitude fit

direct determination of Wilson coeff.

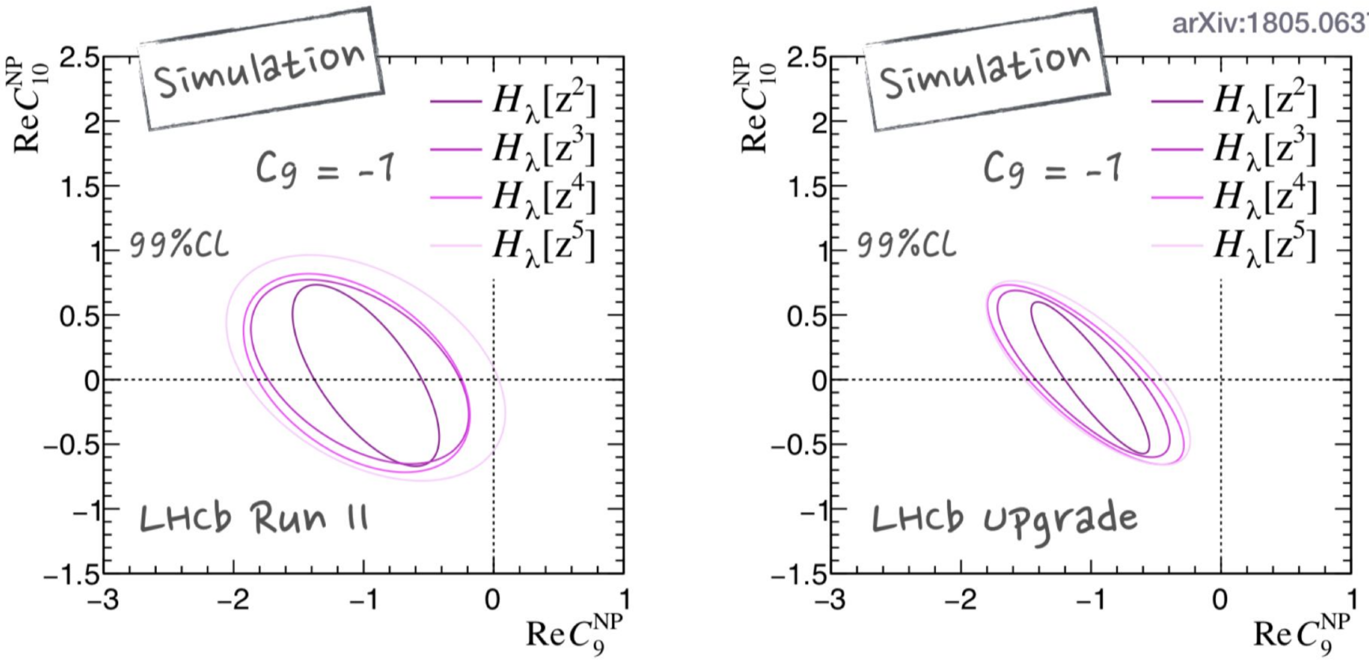
(include branching ratio information via an extended ML fit to signal yield)



Amplitude analysis B→ K*mm

- Studying the **order of the polynomial** allows to inspect charm-loop effects

arXiv:1805.06378



- Uncertainty (slightly) **increase** with the order of the polynomial
- Modeling of the charm-loop → main **systematic**
- Statistical uncertainty on the Wilson coefficients saturates already after Run II due to **form factor uncertainties**

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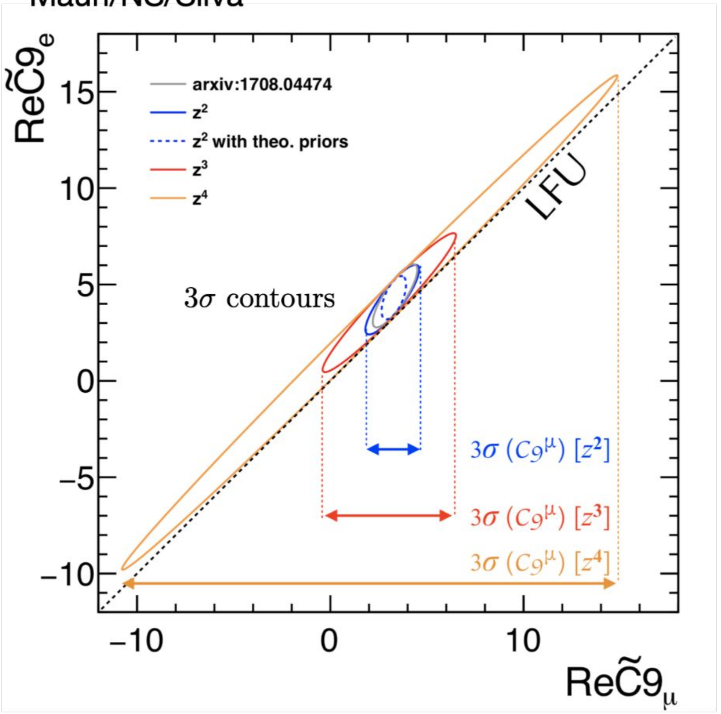
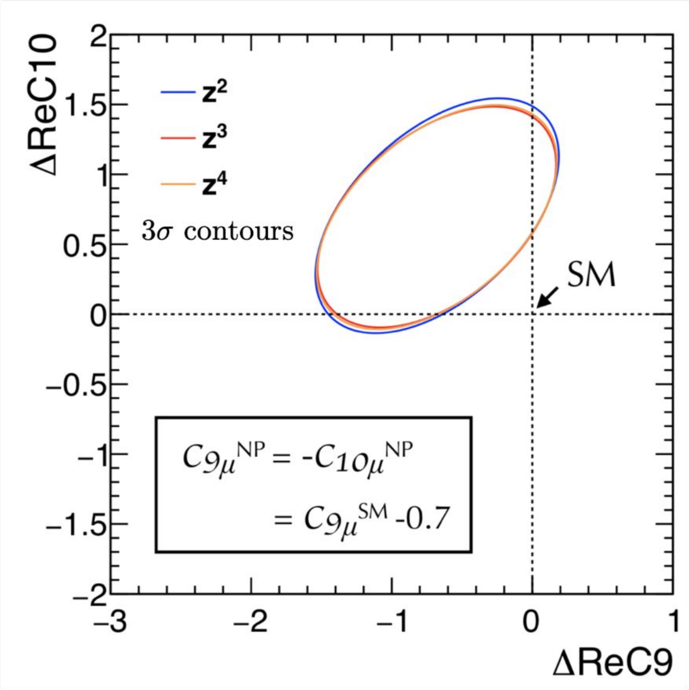
DWC -- LFU Test

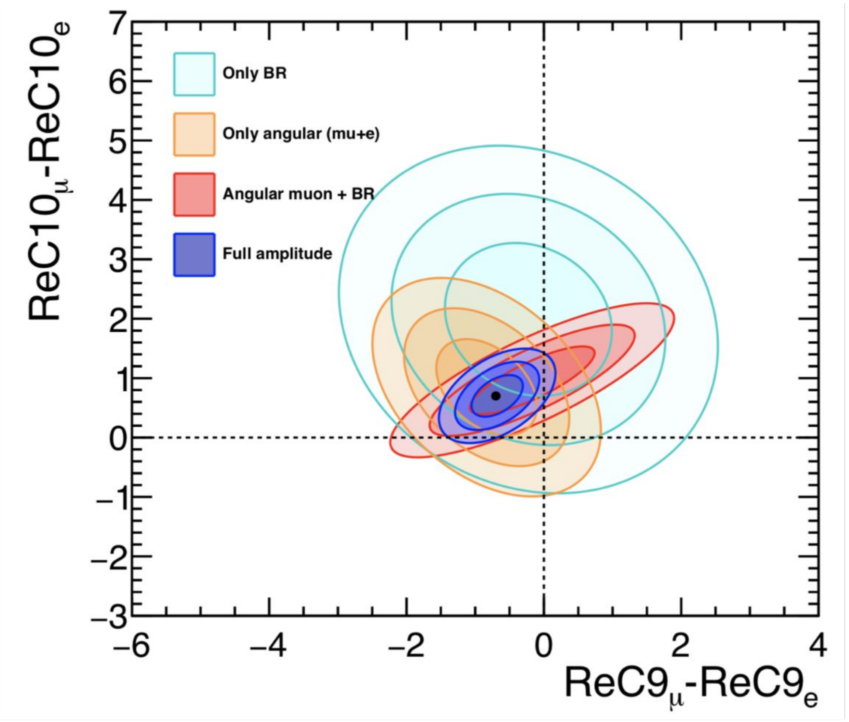
Mauri/NS/Silva





- Simultaneous fit of electron and muons allows to cancel theory uncertainty
- Robust experimental procedure since most of the parameters are “fixed” from the high statistics muons —> only two free parameters in the electron sample (in addition to few nuisance parameters)

DWC -- LFU Test

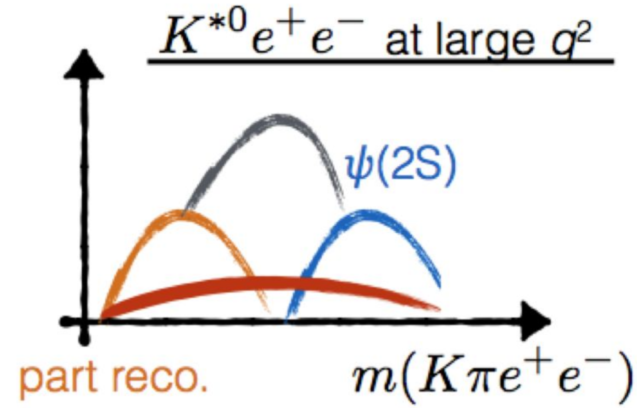


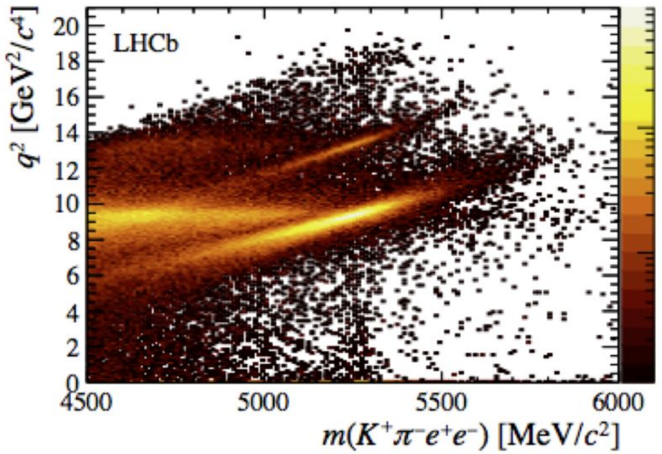
- The Amplitude it of $B \to K^* \ell\ell$ includes all information of angular observables and $R(K^*)$
- It is insensitive on theory parameters

$R_{K^{(*)}}$ at high-q^2

- Very little rate for $q^2 < 1.0$ GeV^2 (no photon pole)

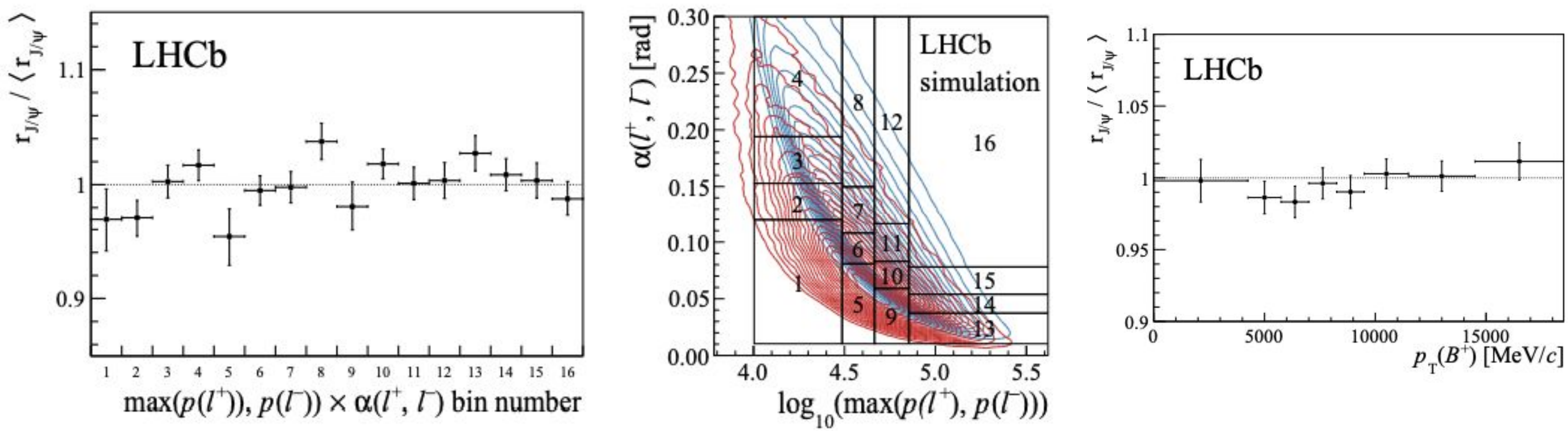
- Working to add high q^2 bin – difficulty same for R_K and R_{K^*}
  - Rare decays with higher K* resonances can leak into signal region from below
  - $\psi(2S)K^*$ decays can leak into signal region on the upper side
  - Signal sandwiched between these and hence difficult to fit reliably





Measuring $r_{J/\psi}$

Measuring the single ratio $r_{J/\psi}$ is one of the main cross check $r_{J/\psi} = 0.981 \pm 0.020$

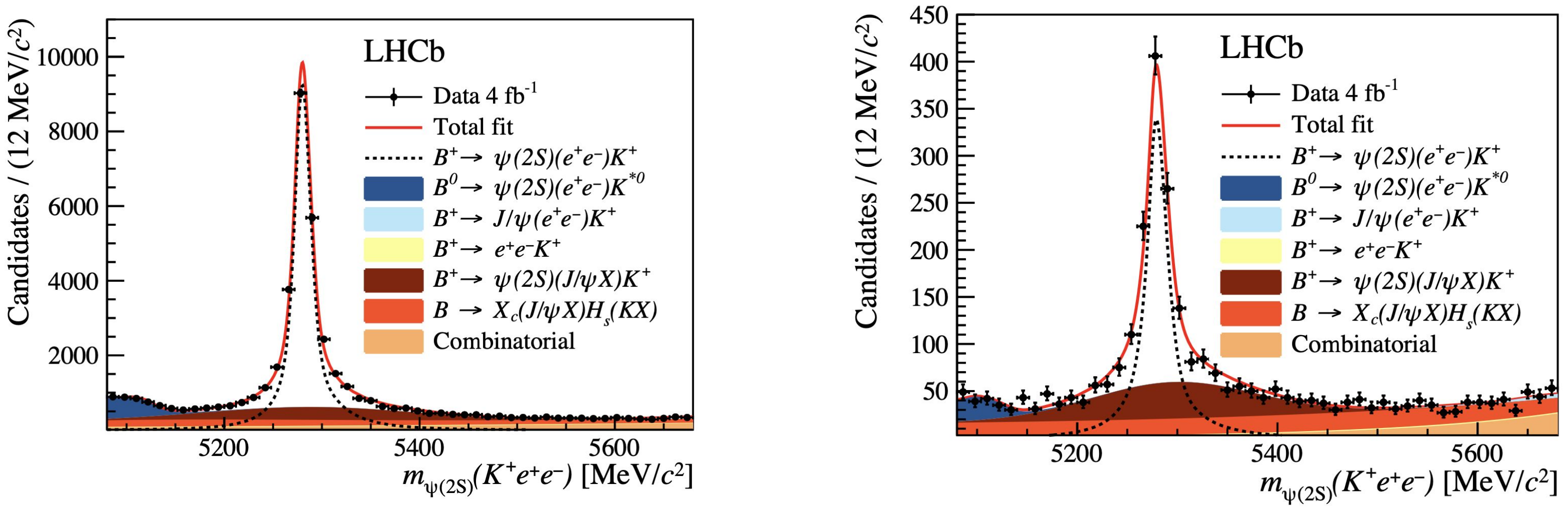


- We mesure $r_{J/\psi}$ as a function of many variables to test if we observe a dependence of the kinematics
- We also measure $r_{J/\psi}$ as a function of the opening angle and the min momentum of the leptons to maximise the overlap with the control channel

Measuring $R_{\psi(2S)}$

The measurement of $r_{J/\psi}$ is systematics dominating since it is a single ratio, another important cross check is the double ratio $R_{\psi(2S)}$:

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 0.997 \pm 0.011$$

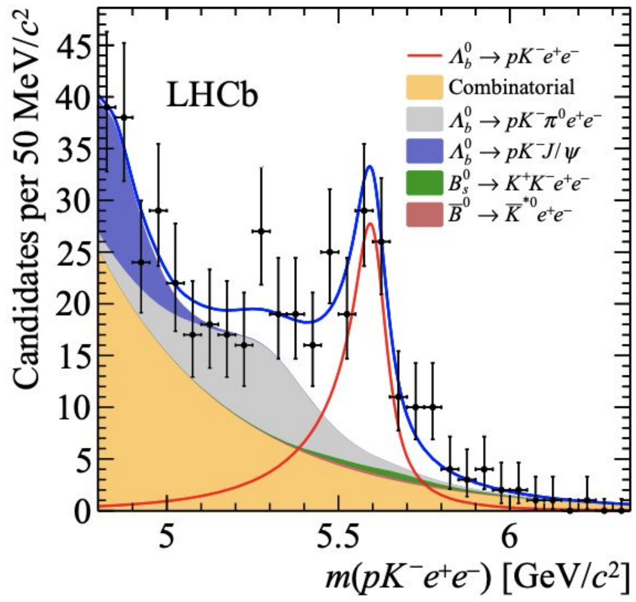


Other b →sll LFU tests at LHCb

- Other LFU tests in b→sll at LHCb show deviation that are numerically coherent with the other observations

$$R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^- e^+ e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to e^+ e^-))} \Big/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^- \mu^+ \mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+ \mu^-))}$$

$$R_{pK}\big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 0.86\,^{+0.14}_{-0.11} \pm 0.05$$



“Global” fits from theory groups

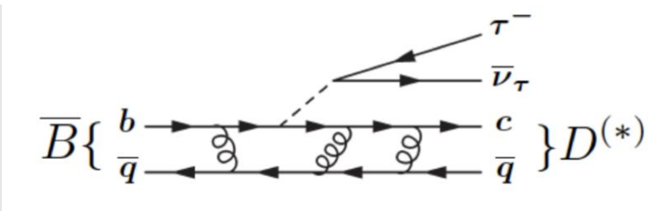
M. Algueró et al. arXiv: 2104.08921

	All				LFUV	
1D Hyp.	Best fit	1 σ	Pull_{SM}	p-value	1 σ	Pull_{SM}
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.06	$[-1.20, -0.91]$	7.0	39.5 %	$[-1.06, -0.60]$	4.0
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.44	$[-0.52, -0.37]$	6.2	22.8 %	$[-0.46, -0.29]$	4.6
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}$	-1.11	$[-1.25, -0.96]$	6.5	28.0 %	$[-2.13, -0.96]$	3.0
$\mathcal{C}_{9\mu}^{\text{NP}} = -3\mathcal{C}_{9e}$	-0.89	$[-1.03, -0.75]$	6.7	32.2 %	$[-0.78, -0.44]$	4.0

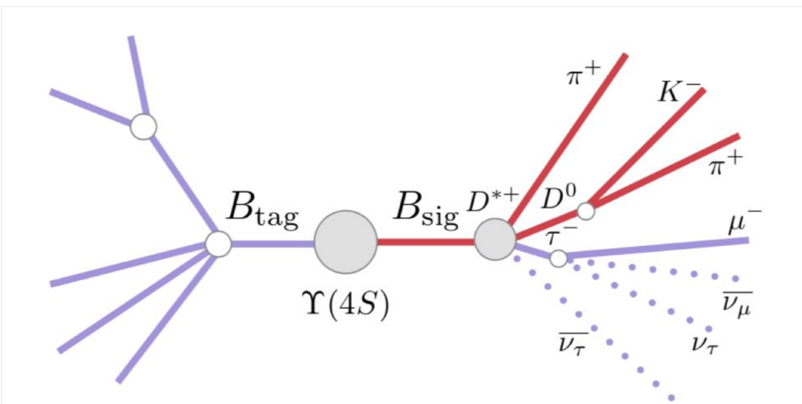
Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9'^{bs\mu\mu}$	$+0.39^{+0.27}_{-0.26}$	1.5σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.14^{+0.13}_{-0.13}$	1.0σ
$C_{10}'^{bs\mu\mu}$	$-0.10^{+0.17}_{-0.16}$	0.6σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.04^{+0.10}_{-0.10}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.34^{+0.16}_{-0.16}$	2.1σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$-0.01^{+0.12}_{-0.12}$	0.1σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

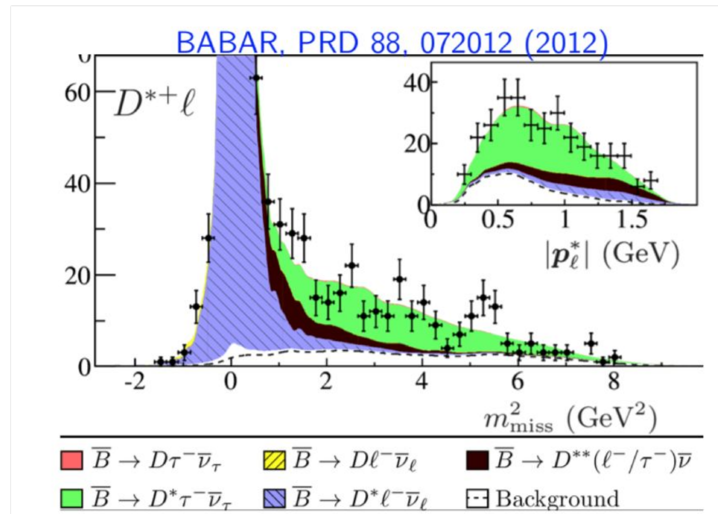
Even only considering “clean” observables 4.7sigmas wrt SM!

Semitauonic



$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)} = \frac{Signal}{Normalization}$$

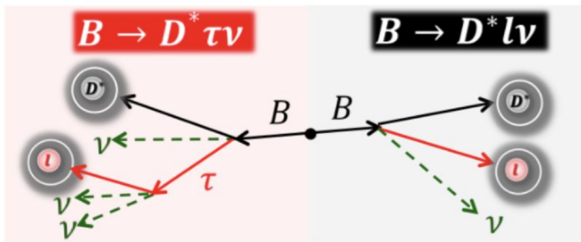




- B-factories exploit the fact that B_{sig} momentum
- B-factories use the electron, muon and hadronic modes
- LHCb only uses $\tau \to \mu 2\nu$ and $\tau \to 3\pi\nu$
- B-factories have cleaner events, while LHCb larger statistics

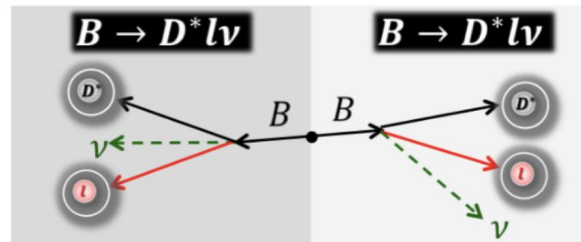
Semitauonic

Semitauonic signal-side decay and semileptonic tag-side.



Numerator in $\mathcal{R}(D^*)$

Normalization events are double semileptonic decays.



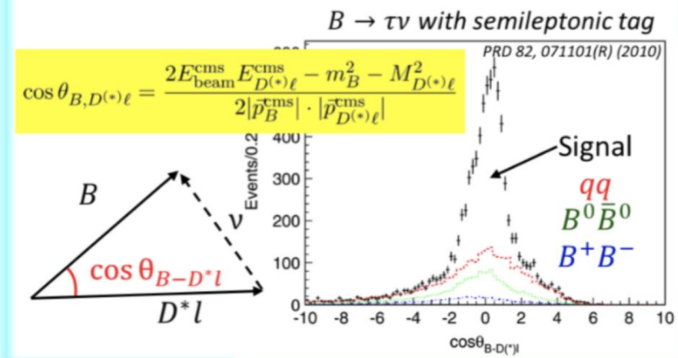
Denominator in $\mathcal{R}(D^*)$

D^* reconstruction:

- $D^{*+} \to D^0\pi^+, D^+\pi^0$ ($\sim 100\%$)
  - D^0: 10 modes ($\sim 37\%$)
  - D^+: 5 modes ($\sim 22\%$)

Tag semileptonic B-decay: Combine D^{*+} and oppositely-charged lepton candidates and calculate the cosine of the angle between the B momentum and the D^*l in the $\Upsilon(4S)$ frame.

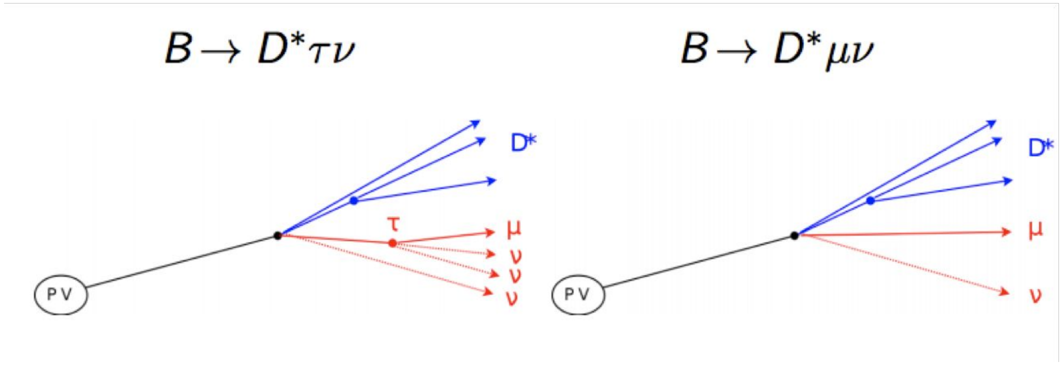
$\Rightarrow$



✓ **tag candidates: $\cos\theta_{B\text{-}D^*\ell} \in [-1, 1]$**

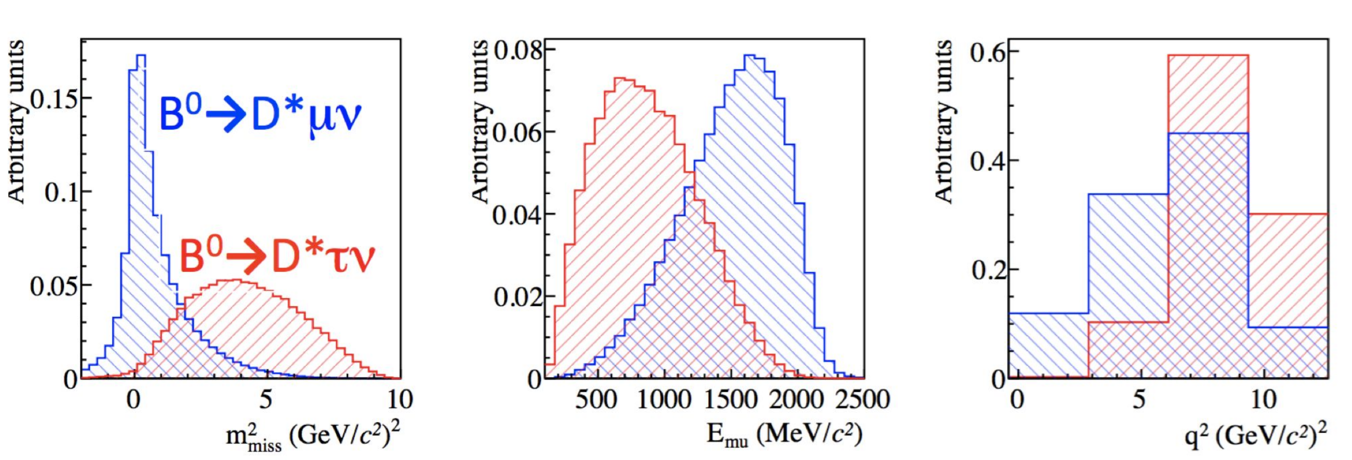
Image credits: Y. Sato (Nagoya)

Test of LFU in b→ clν

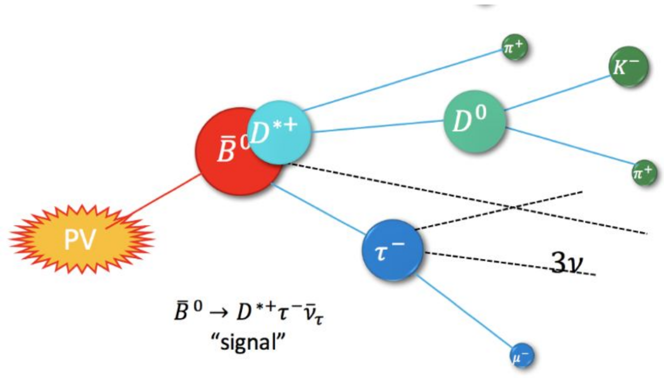


$$(\gamma\beta_{\hat{z}})_B \simeq (\gamma\beta_{\hat{z}})_{D^*\mu} \Rightarrow (p_{\hat{z}})_B = \frac{m_B}{m(D^*\mu)}(p_{\hat{z}})_{D^*\mu}$$

- Fit of E^* and missing mass using template from the simulation tuned with data
- Background from $B \to D^* D_{(s)}$ and from $B \to D^{**} l \nu$ taken from control regions

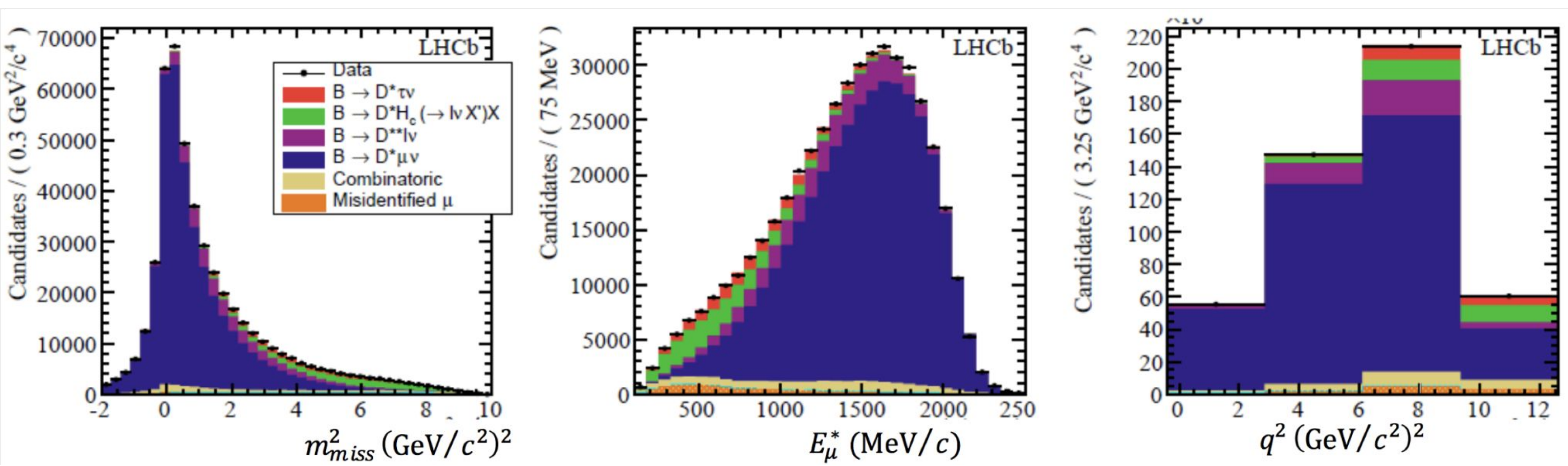


Semitauonic - LHCb

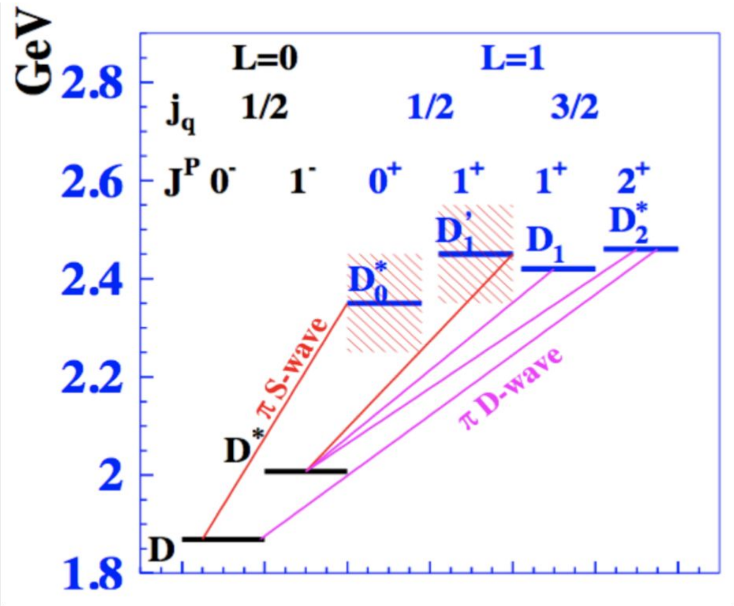


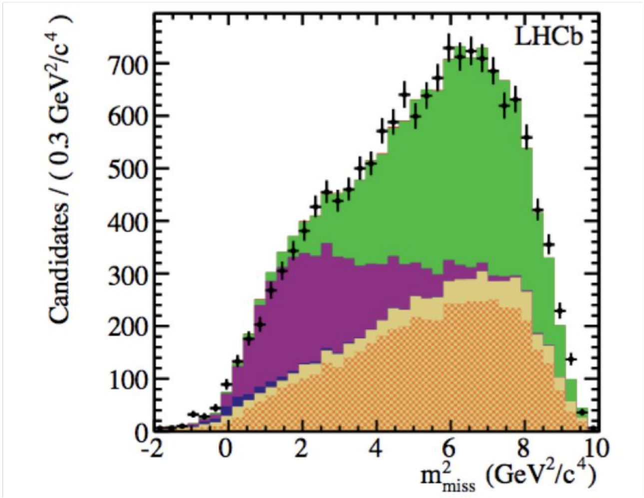
$$(\gamma\beta_z)_{\bar{B}} = (\gamma\beta_z)_{D^*\mu} \quad \Longrightarrow \quad (p_z)_{\bar{B}} = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

- B-direction given by PV-SV
- Full fit of the MM, E*, q²
- Muon, tau modes and bkg fit simultaneously



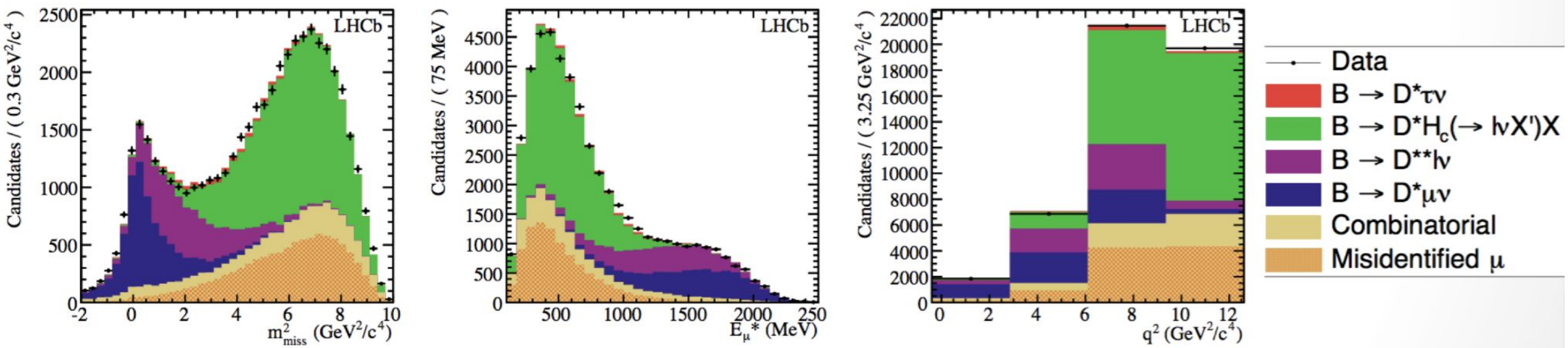
Semitauonic - LHCb





- Large contribution from excited D** states
- Narrow states ($D_1^{(')}$ and D_2^*) fit directly from data B->D*pi lv used as a control sample
- Higher D** excited states also fit from data and B->D pipi lv used as a control channel

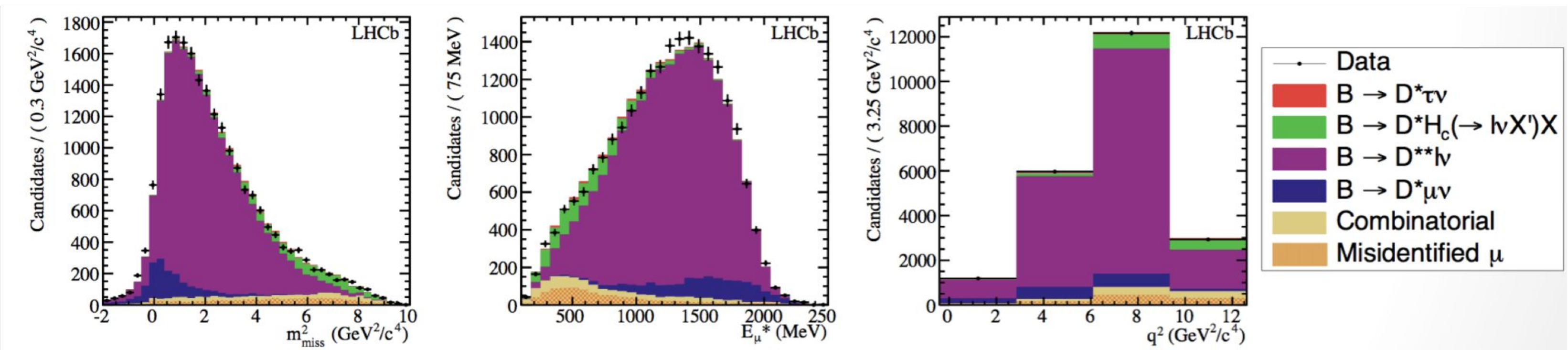
Semitauonic - LHCb



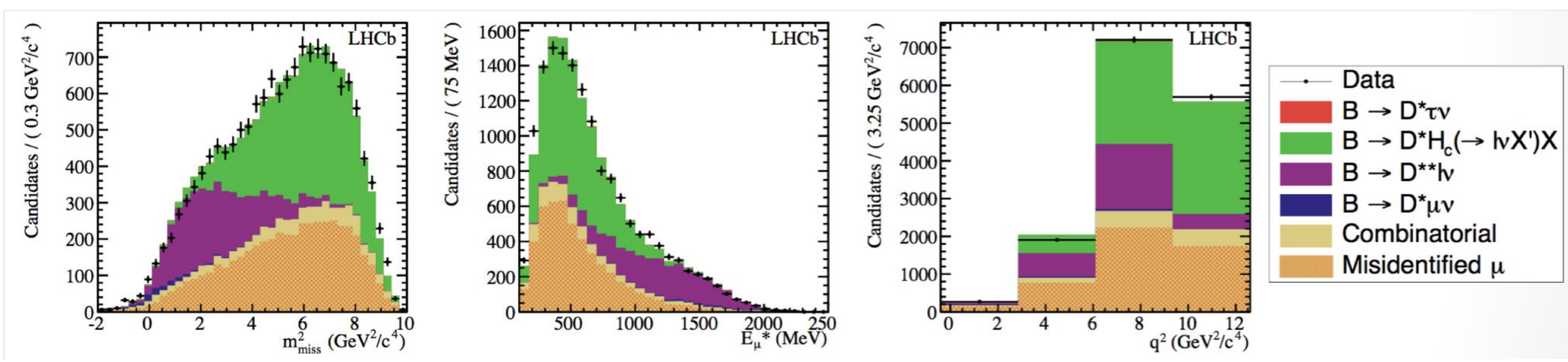
- As usual charm is a background for tau
- Bkg from D_s->tau nu, D ->K lv fit directly from data
- Control sample obtained reconstructing B->D* K lv

Semitauonic - LHCb

- Fit to the control sample “D*pi l”

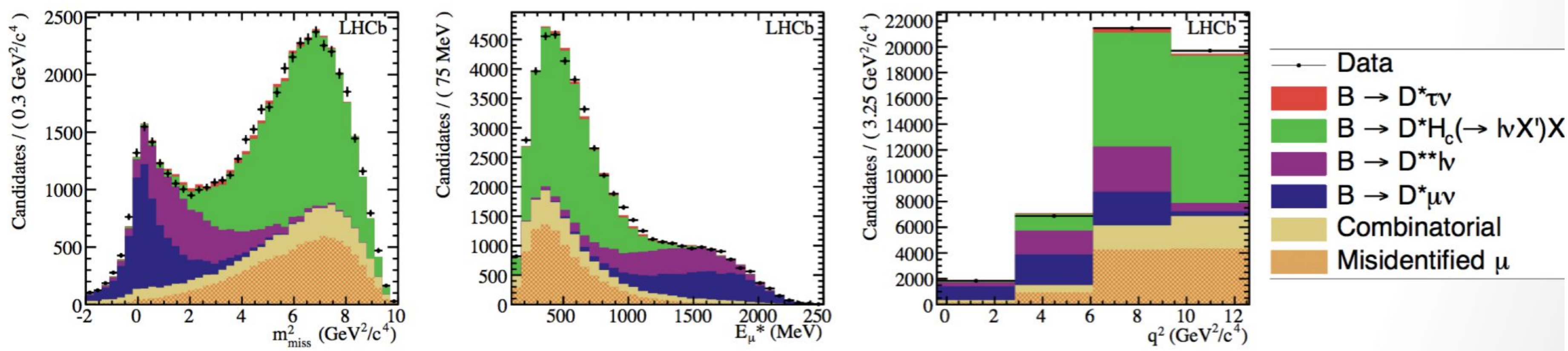


- Fit to the control sample “D*pipi l”



Semitauonic - LHCb

- Fit to the control sample "D*K l"



- Similar simulated sample for B->DD$_s$ with D$_s$->tau v

Test of LFU in b→ clν

$\tau \rightarrow 3\pi\nu$

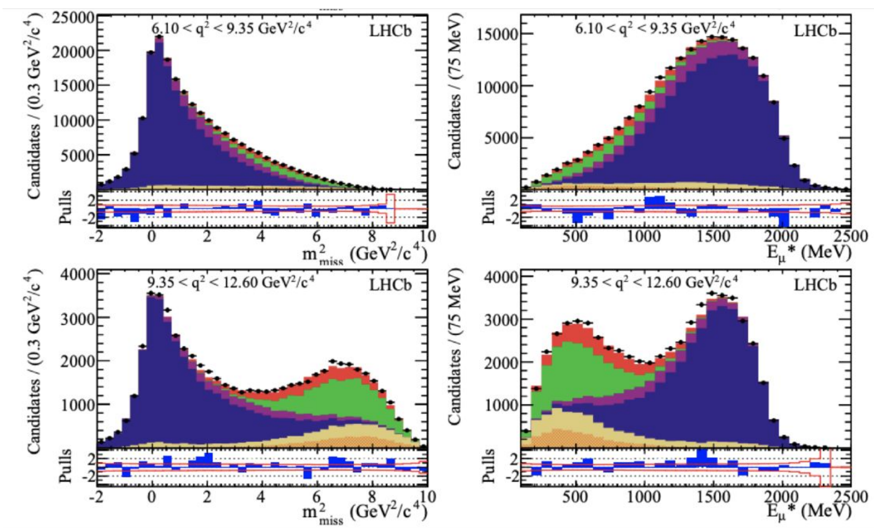
LHCb Coll., Phys. Rev. D 97, 072013 (2018)

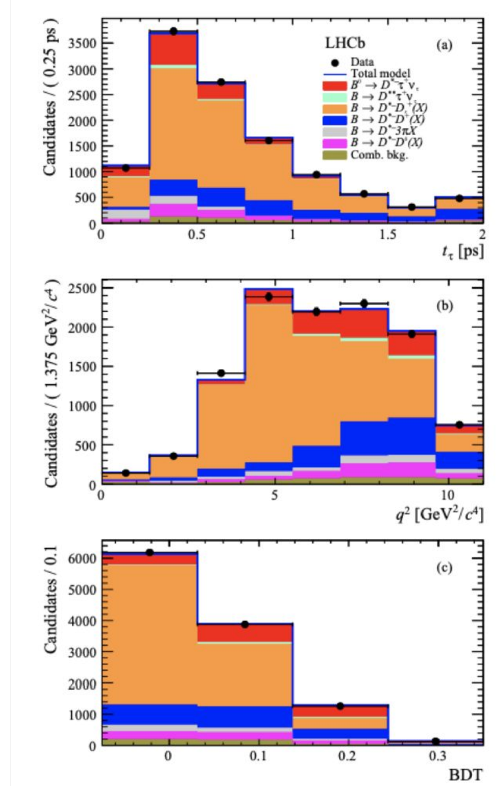
$$R(D^*)_{\tau\rightarrow 3\pi\nu} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

$\tau \rightarrow \mu 2\nu$

LHCb Coll., Phys.Rev.Lett. 115 (2015) no.11, 111803

$$R(D^*)_{\tau\rightarrow \mu 2\nu} = 0.336 \pm 0.027 \pm 0.030$$





SM Prediction average (HFLAV 2019)

$$R(D^*)_{SM} = 0.254 \pm 0.05$$

Semitauonic - LHCb

Systematics uncertainty for R(D*) in LHCb

Model uncertainties		Absolute size ($\times 10^{-2}$)
Simulated sample size		2.0
Misidentified μ template shape		1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors		0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	Background modelling; depends on control sample size	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$		0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections		0.4
Corrections to simulation		0.4
Combinatorial background shape		0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors		0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction		0.1
Total model uncertainty		**2.8**
Normalization uncertainties		**Absolute size ($\times 10^{-2}$)**
Simulated sample size		0.6
Hardware trigger efficiency		0.6
Particle identification efficiencies		0.3
Form-factors		0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$		< 0.1
Total normalization uncertainty		**0.9**
Total systematic uncertainty		**3.0**

Semitauonic