Heavy Flavour Anomalies

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Outline

- Introduction and Motivation.
- The path to the $b \to s\ell\ell$ anomalies... why there? why now?
- Updated Global fit: Results 1D, 2D, 6D.
- Hadronic uncertainties on a nutshell
- Disentangling scenarios of New Physics? A glance into the future.
- Example of a Z' (not a model)
- Other anomalies... $b \to c\tau\nu$
- Scale of New Physics.
- Conclusions

Even if the SM is extremely successful theory most likely is an effective theory, it does not explain...

- why 3 generations of fermions? why their masses are so hierarchical.
- origin of the Baryon asymmetry in the universe? matter anti-matter asymmetry too small in SM.
- **lack of a candidate of the dark matter observed in the Universe**
- ...

$\Downarrow$

a more fundamental theory with new degrees of freedom (new particles)

This new theory defines what is usually called **New Physics**

Two types of searches for New Physics:

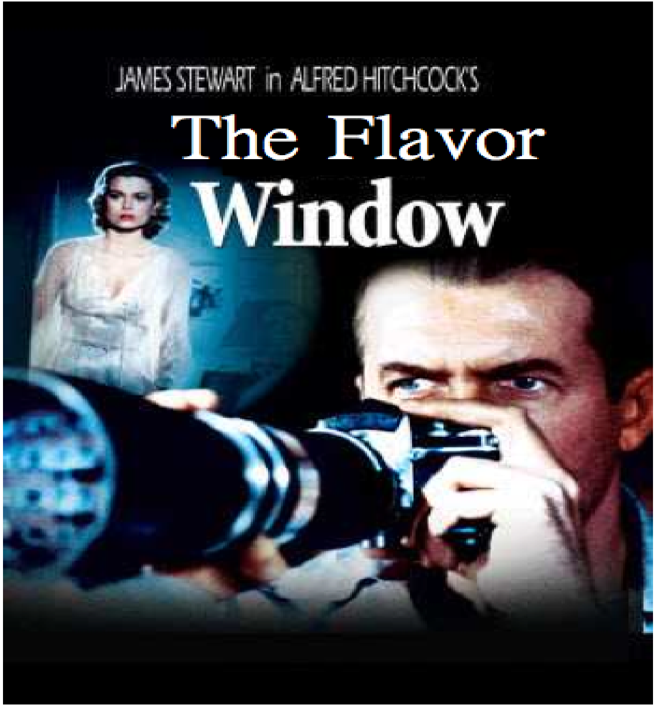
- **DIRECT** production of New Particles: so far nothing new....besides SM Higgs. It needs **Energy**.
- **INDIRECT** or VIRTUAL production of New Particles affecting (i.e. loops) couplings & **decays**
  Target of **Flavour Physics** $\Rightarrow$ Energy scales not directly accessible at accelerators.

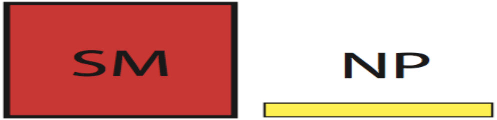
Our “pets” and how we play with them...

List of B mesons

B mesons

Particle	Symbol	Anti-particle	Quark content	Charge	Isospin (I)	Spin and parity (J^P)	Rest mass (MeV/c^2)	S	C	B'	Mean lifetime (s)
Strange B meson	B_s^0	$\bar{B}_s^0$	$s\bar{b}$	0	0	0^-	5,366.3 ±0.6	−1	0	+1	$1.470^{+0.027}_{-0.026} \times 10^{-12}$
B meson	B^0	$\bar{B}^0$	$d\bar{b}$	0	½	0^-	5,279.53 ±0.33	0	0	+1	$(1.530 \pm 0.009) \times 10^{-12}$
Charmed B meson	B_c^+	B_c^-	$c\bar{b}$	+1	0	0^-	6,276 ±4	0	+1	+1	$(0.46 \pm 0.07) \times 10^{-12}$
B meson	B^+	B^-	$u\bar{b}$	+1	½	0^-	5,279.15 ±0.31	0	0	+1	$(1.638 \pm 0.011) \times 10^{-12}$



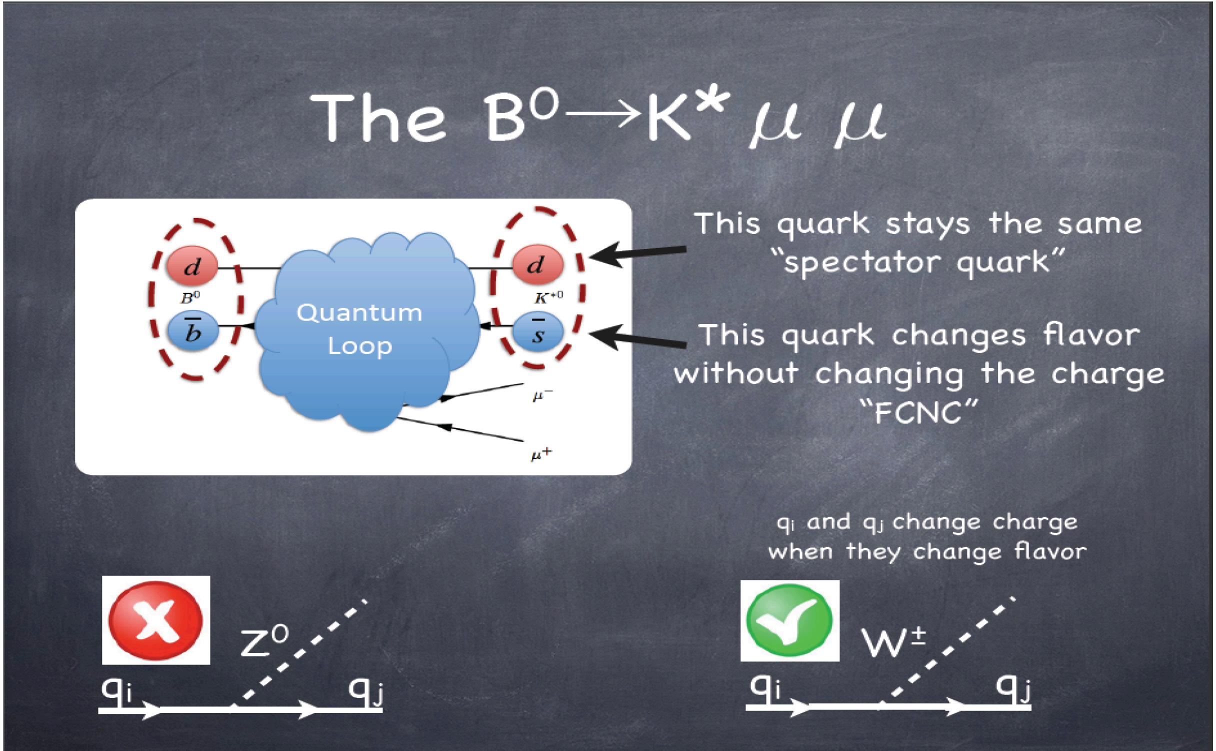


SM expected to be dominant
(tree dominated)
[semi/leptonic dec.] Metrology of SM

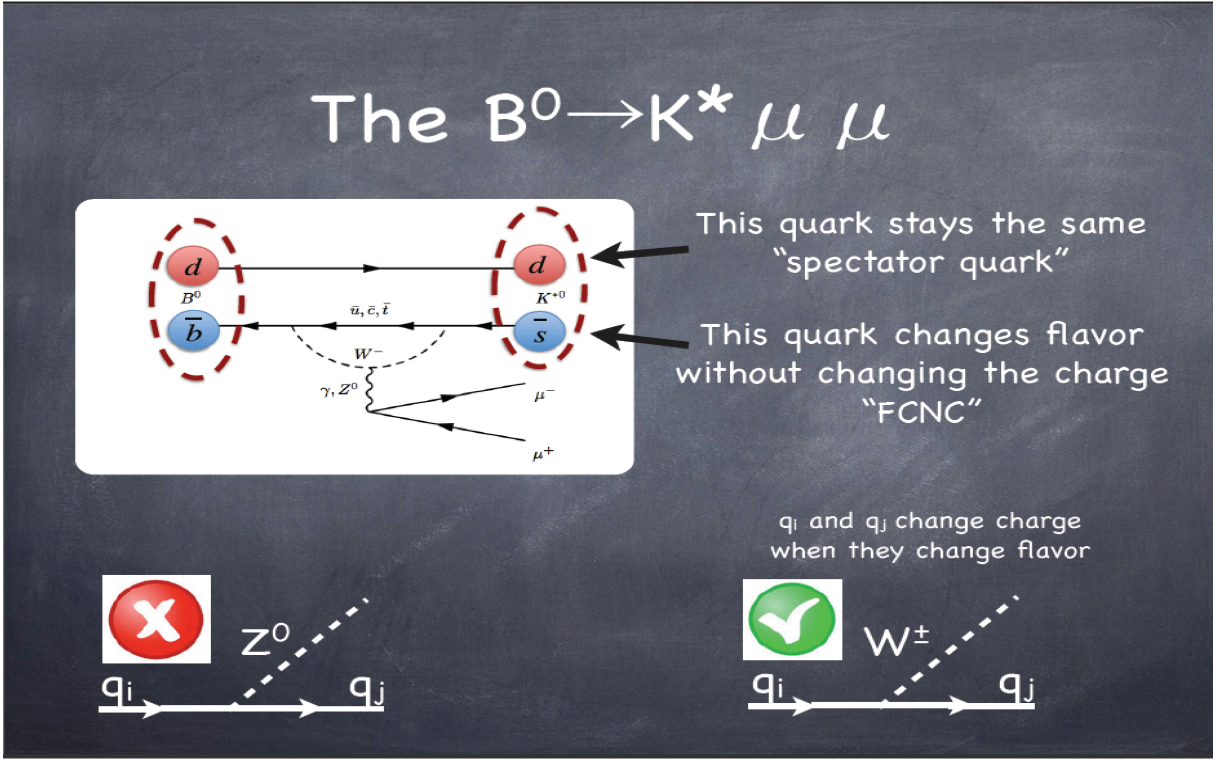
SM and NP competing
(loop dominated)
[rare processes] Constraints on NP
FCNC Forbidden in SM at tree level

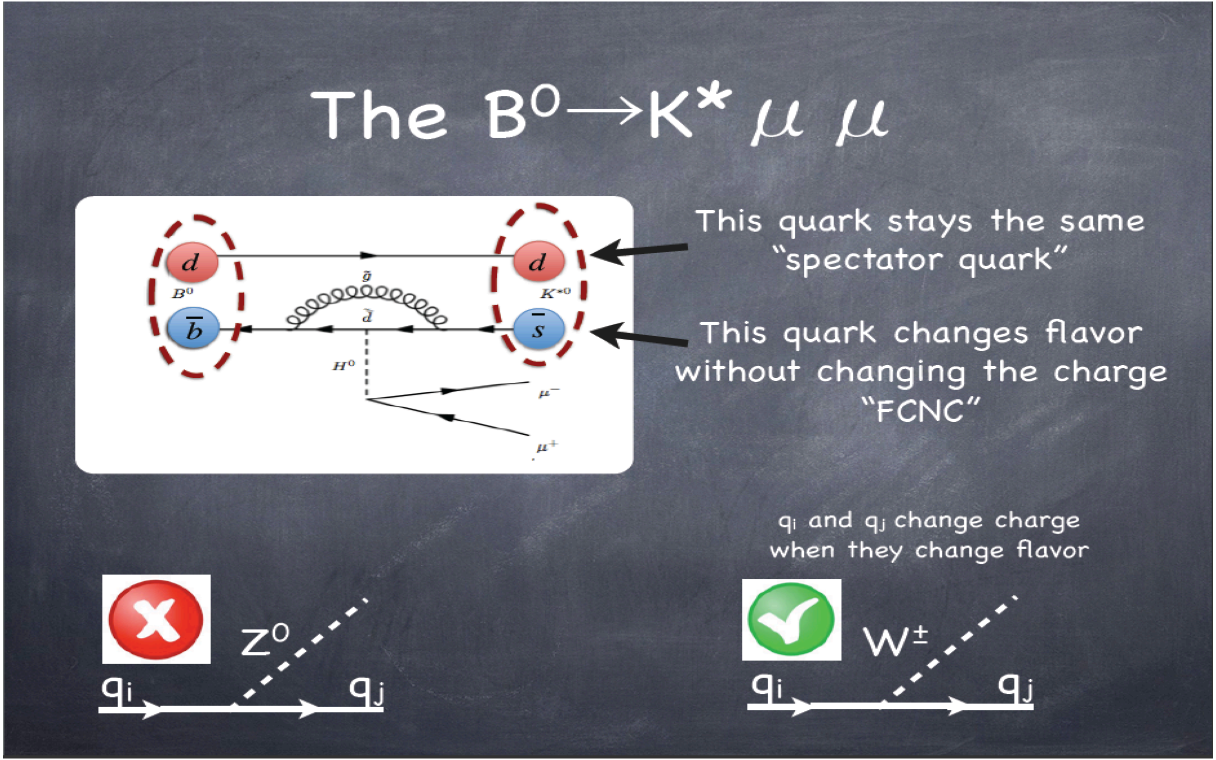
Subclass of observables (LFUV)
with little hadronic unc. **IN SM.**
$\rightarrow$ Smoking guns of NP

A relevant example of FCNC process



A relevant example of FCNC process





The $B^0 \to K^* \mu\, \mu$
d
B^0
$\bar{b}$
$\tilde{g}$
$\tilde{d}$
H^0
d
K^{*0}
$\bar{s}$
μ^-
μ^+
This quark stays the same
"spectator quark"
This quark changes flavor
without changing the charge
"FCNC"
q_i and q_j change charge
when they change flavor
Z^0
q_i
q_j
$W^\pm$
q_i
q_j

Goal of this talk

Messages to take home of this talk:

For the first time we see Coherence on a large set of deviations/anomalies

Nature seems to point towards first signals of violation of lepton flavour universality

...SM predicts LFU: interactions between gauge bosons and leptons being the same for different lepton families.

... soon we will have more observables to confirm it.

Not my goal HERE to focus on a specific UV completion but to SHOW that there is a **SIGNAL**.

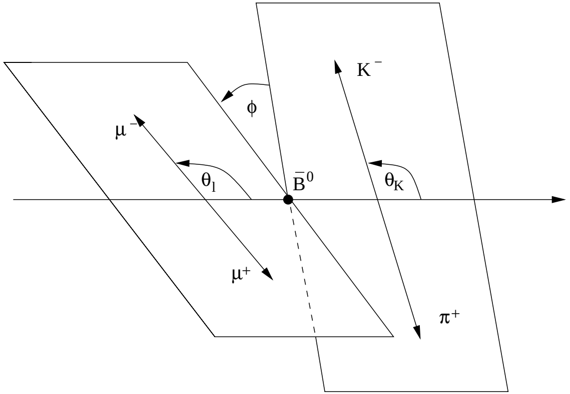
The path

to the anomalies

Why now? why there?

The starting point: Angular distribution of $B \to K^*(\to K\pi)\mu\mu$

4-body angular distribution $\mathbf{\bar{B}_d} \to \mathbf{\bar{K}^{*0}}(\to \mathbf{K}^-\pi^+)\mathbf{l}^+\mathbf{l}^-$ with three angles, invariant mass of lepton-pair q^2.



θ_ℓ: Angle of emission between $\bar{K}^{*0}$ and μ^- in di-lepton rest frame.
$\theta_\mathbf{K}$: Angle of emission between $\bar{K}^{*0}$ and K^- in di-meson rest frame.
ϕ: Angle between the two planes.

$\mathbf{q^2}$: dilepton invariant mass square.

$$\frac{d^4\Gamma(\bar{B}_d)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} \sum_i J_i(q^2) f_i(\theta_\ell, \theta_K, \phi)$$

$J_i(q^2)$ function of transversity (helicity) amplitudes of K*: $A^{L,R}_{\perp,\|,0}$ but also A_t, A_S

$A^{L,R}_{\perp,\|,0}$= $\mathcal{C}_i$ (short) $\times$ Hadronic quantities (long)

The differential distribution splits in J_i coefficients:

$$J(q^2, \theta_l, \theta_K, \phi) =$$
$$J_{1s} \sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l + J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi$$
$$+J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_K \sin\theta_l \cos\phi + (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l$$
$$+J_7 \sin 2\theta_K \sin\theta_l \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi \,.$$

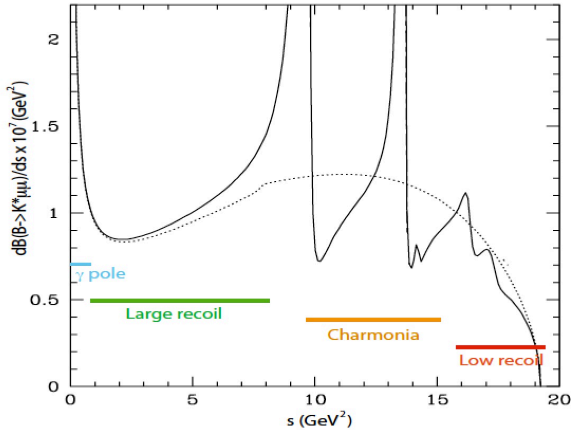
Example:

$$\begin{aligned} J_{1s} &= \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right] + \frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R^*} + A_\parallel^L A_\parallel^{R^*}\right) \\ J_{6s} &= 2\beta_\ell\left[\mathrm{Re}(A_\parallel^L A_\perp^{L^*}) - (L\to R)\right], \quad J_8 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(A_0^L A_\perp^{L^*}) + (L\to R)\right], \end{aligned}$$

- The transverse amplitudes $A_{\perp,\parallel,0}$ are directly related to Helicity Amplitudes of K*:

$$A_{\perp,\parallel} = (H_{+1} \mp H_{-1})/\sqrt{2} \qquad A_0 = H_0$$

Four regions in q^2 for the angular distribution $B \to K^*(\to K\pi)\mu^+\mu^-$

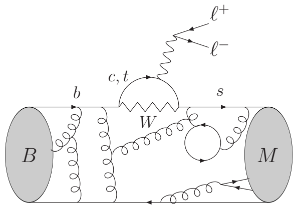


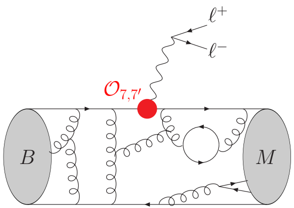
Four regions in q^2:

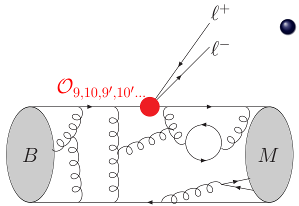
- **very large** K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2): γ almost real.
- **large** K^***-recoil/low-q**^{2}: $E_{K^*} \gg \Lambda_{QCD}$ or $4m_\ell^2 \leq q^2 < 9$ GeV^2: LCSR-FF
- charmonium region ($q^2 = m^2_{J/\Psi}, ...$) betwen $9 < q^2 < 14$ GeV^2.
- **low** K^***-recoil/large-q**^{2}: $E_{K^*} \sim \Lambda_{QCD}$ or $14 < q^2 \leq (m_B - m_{K^*})^2$: LQCD-FF

The amplitude

The framework: $b \to s\ell\ell$ effective Hamiltonian, **Wilson Coefficients**







$$b \to s\gamma^{(*)} : \mathcal{H}^{SM}_{\triangle F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \ldots$$

separate short and long distances ($\mu_b = m_b$)

- $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \left(\bar{\mathbf{s}}\sigma^{\mu\nu}\mathbf{P_R b}\right) \mathbf{F}_{\mu\nu}$ [real or soft photon]
- $\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{\mathbf{s}}\gamma_\mu \mathbf{P_L b})\ (\bar{\ell}\gamma^\mu \ell)$
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{\mathbf{s}}\gamma_\mu \mathbf{P_L b})\ (\bar{\ell}\gamma^\mu \gamma_5 \ell)$

$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3$$

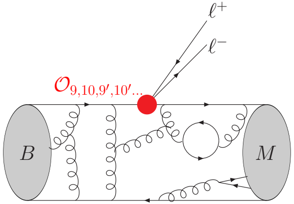
NP changes short-distance $\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP}$ for SM or involve additional operators $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\mathcal{O}_{7'} \propto (\bar{s}\sigma^{\mu\nu} P_L\, b) F_{\mu\nu}$, $\mathcal{O}_{9'} \propto (\bar{s}\gamma_\mu P_R\, b)(\bar{\ell}\gamma^\mu \ell)$ ....
- (Pseudo)scalar ($W \to H^+$) $\mathcal{O}_S \propto (\bar{s}P_R b)(\bar{\ell}\ell)$, $\mathcal{O}_P \propto (\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)$
- Tensor operators ($\gamma \to T$) $\mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5) b\ \bar{\ell}\sigma_{\mu\nu}\ell$

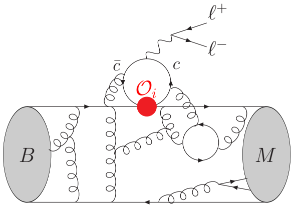
The framework: Hadronic structure of $B \to K^*\ell\ell$

$$A(B \to K^*\ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu) \bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$

Form factors (local)



Charm loop (non-local)



$\boxed{1}$ Local contributions: 7 form factors $\Rightarrow V, A_{0,1,2,}, T_{1,2,3}$

$$\begin{aligned} A_\mu &= -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle V_\lambda | \bar{s}\sigma_{\mu\nu} P_R b | B \rangle + \mathcal{C}_9 \langle V_\lambda | \bar{s}\gamma_\mu P_L b | B \rangle \\ B_\mu &= \mathcal{C}_{10} \langle V_\lambda | \bar{s}\gamma_\mu P_L b | B \rangle \qquad \lambda: \; K^* \text{ helicity} \end{aligned}$$

$\boxed{2}$ Non-local contributions (charm loops): hadronic contribs.

T_μ contributes like $\mathcal{O}_{7,9}$, but depends on q^2 and external states

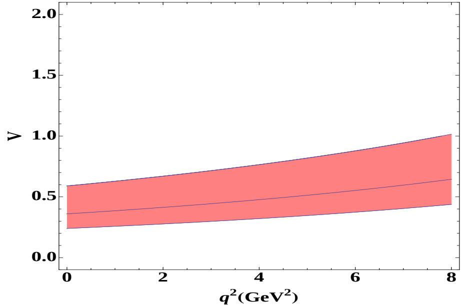
Form Factors to parametrize $B \to M$

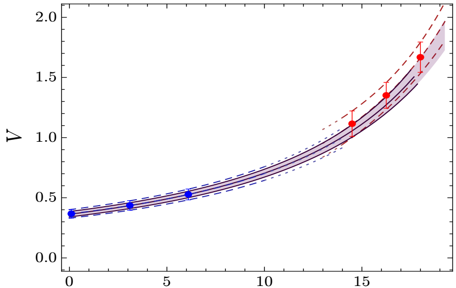
$\Rightarrow$ Different sets of form factors available: KMPW (LCSR, low q^2) or BSZ (fit LCSR + lattice).

- low K^* recoil: lattice, with correlations [Horgan, Liu, Meinel, Wingate]
- large K^* recoil: B-meson Light-Cone Sum Rule,
  - large error bars and no correlations [Khodjamirian, Mannel, Pivovarov, Wang]
  - reduce uncertainties and restore correlations among form factors using EFT correlations arising in $m_b \to \infty$, e.g., at large K^* recoil

$$\xi_\perp = \frac{m_B}{m_B + m_{K^*}} V = \frac{m_B + m_{K^*}}{2E_{K^*}} A_1 = T_1 = \frac{m_B}{2E_{K^*}} T_2 \qquad + O(\alpha_s, \Lambda/m_b) \text{ corr}$$

- Alternatively: fit to K^*-meson LCSR + lattice, small errors bars, correlations [Bharucha, Straub, Zwicky]





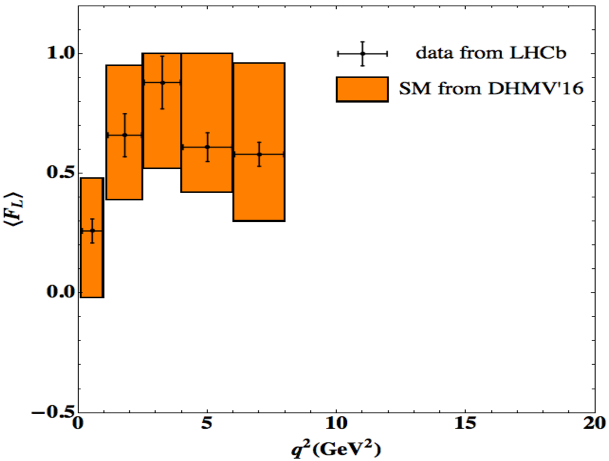
Traditional experimental approach to

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

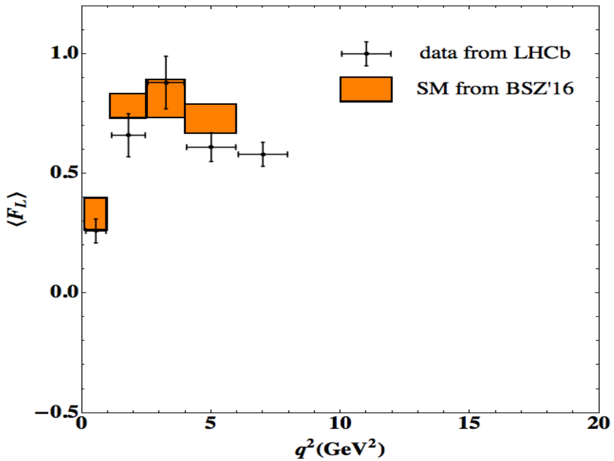
For a longtime only $\frac{dB}{dq^2}, F_L, A_{\rm FB}$ were the target of traditional analysis.

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = -\left(\frac{3}{4}\mathbf{F_L}\sin^2\theta_\ell + \frac{3}{8}(1-\mathbf{F_L})(1+\cos^2\theta_\ell) + \mathbf{A}_{\rm FB}\cos\theta_\ell\right)\frac{\mathbf{d\Gamma}}{\mathbf{dq^2}}$$

FF: KMPW



FF: BSZ



....in these observables hadronic uncertainties mask any possible sign of New Physics.

Two key observations:

- **THEORY**: At leading order in $1/m_b$, α_s and large-recoil ($E_{K^*} \to \infty$) FF fulfill:

$$\frac{m_B}{m_B+m_V}\mathbf{V}(\mathbf{q^2}) = \frac{m_B+m_V}{2E}\mathbf{A_1}(\mathbf{q^2}) = \mathbf{T_1}(\mathbf{q^2}) = \frac{m_B}{2E}\mathbf{T_2}(\mathbf{q^2}) = \xi_\perp(\mathbf{q^2})$$

$$\frac{m_B+m_V}{2E}\mathbf{A_1}(\mathbf{q^2}) - \frac{m_B-m_V}{m_B}\mathbf{A_2}(\mathbf{q^2}) = \frac{m_B}{2E}\mathbf{T_2}(\mathbf{q^2}) - \mathbf{T_3}(\mathbf{q^2}) = \xi_\parallel(\mathbf{q^2})$$

consequently the transversity amplitudes:

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

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

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

- **EXPERIMENT**: One can get access to new observables using the "folding technique". Identify $\phi \leftrightarrow -\phi$ and $\theta_\ell \leftrightarrow \pi-\theta_\ell$ leads to

$$d\Gamma = d\Gamma(\hat{\phi}) + d\Gamma(-\hat{\phi}) + d\Gamma(\hat{\phi}, \pi-\hat{\theta}_\ell) + d\Gamma(-\hat{\phi}, \pi-\hat{\theta}_\ell)$$

A new approach: new observables

Optimized observables: P_i

One can construct a new type of observables out of $A_{\perp,\|,0}$ based on two criteria:

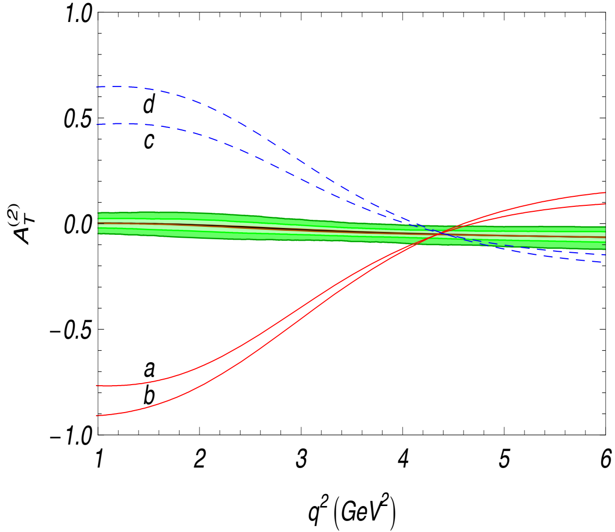
$\boxed{1}$ Exact Cancelation at LO of the SFF ($\xi_{\perp,\|}$):

$$A_T^{(2)} = P_1 = \frac{|A_\perp|^2 - |A_\||^2}{|A_\perp|^2 + |A_\||^2} = \mathcal{O}(\alpha_s \xi_\perp) + \ldots$$

compared to

$$F_L = \mathcal{O}(\xi_\perp^2/\xi_\|^2)$$

- The suppression of $H_{+1} = (A_\perp + A_\|)/\sqrt{2} \simeq 0$ due to LHS of SM implies $|A_\perp| \simeq |A_\||$.
- A contribution to C_7' induces a large-deviation (sign-sensitive: positive-down, negative-up).



$\boxed{2}$ Respect the symmetries of the distribution.

Symmetries of the angular distribution $B \to K^*(\to K\pi)\mu^+\mu^-$

[Egede, Hurth, JM, Ramon, Reece'10]

An important step forward was the identification of the **symmetries** of the distribution:

Transformation of amplitudes leaving distribution invariant.

All the distribution can be rewritten in terms of $n_\| = (A_\|^L, A_\|^{R*})$, $n_\perp = (A_\perp^L, -A_\perp^{R*})$ and $n_0 = (A_0^L, A_0^{R*})$.

Symmetries of Massless Case:

$$n_i' = U n_i = \begin{bmatrix} e^{i\phi_L} & 0 \\ 0 & e^{-i\phi_R} \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \cosh i\tilde{\theta} & -\sinh i\tilde{\theta} \\ -\sinh i\tilde{\theta} & \cosh i\tilde{\theta} \end{bmatrix} n_i \,.$$

Symmetries determine the minimal # observables for each scenario:

$$n_{obs} = 2n_A - n_S \qquad n_{obs} = n_{Ji} - n_{dep}$$

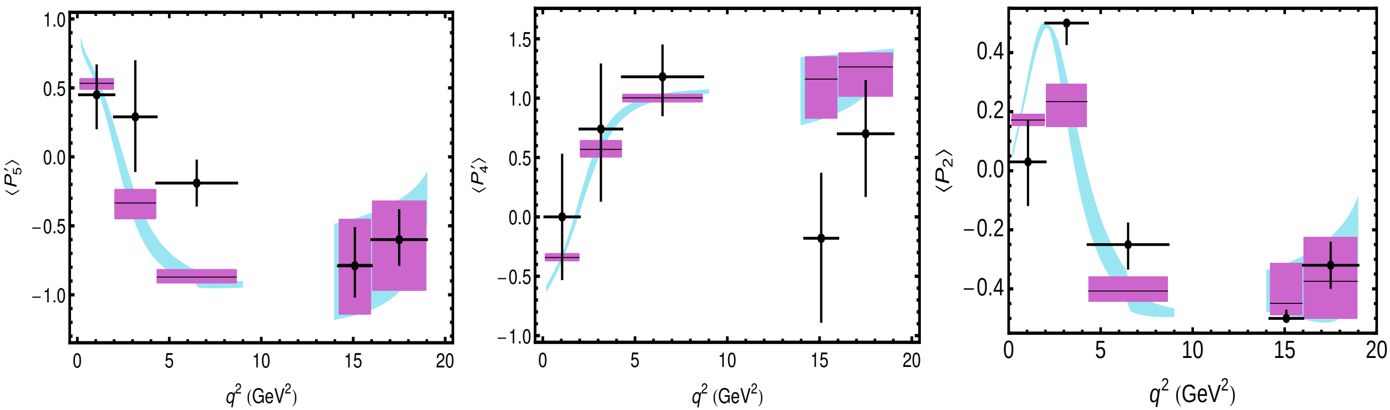
Case	Coefficients J_i	Amplitudes	Symmetries	Observables	Dependencies
$m_\ell = 0,\ A_S = 0$	11	6	4	**8**	3
$m_\ell = 0$	11	7	5	**9**	2
$m_\ell > 0,\ A_S = 0$	11	7	4	**10**	1
$m_\ell > 0$	12	8	4	**12**	0

All symmetries (massive and scalars) were found explicitly later on. [JM, Mescia, Ramon, Virto'12]

Symmetries $\Rightarrow$ # of observables $\Rightarrow$ determine a **basis:** $\Rightarrow \{\frac{dBr}{dq^2}, F_L, P_1, P_2, P_3, P_4', P_5', P_6'\}$

Why so much excitement in Flavour Physics in that year?

First measurement by LHCb of the basis of optimized observables P_i with 1 fb^{-1}:



All the focus was on the optimized observable P_5' that deviated in the bin [4,8.68] GeV^2 near 4σ.

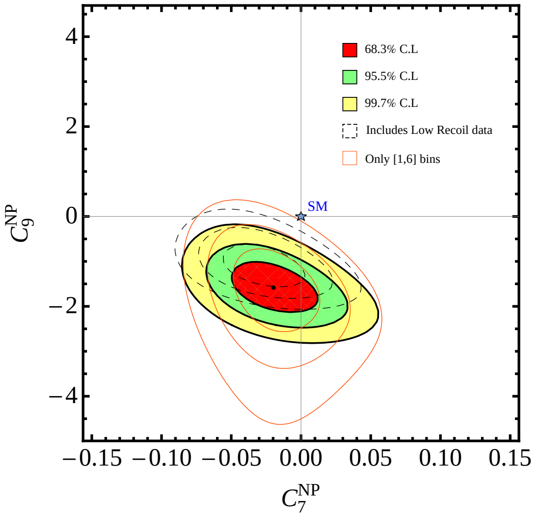
BUT the relevant point......indeed is the COHERENT PATTERN among the relevant observables [S. Descotes-Genon, J.M., J. Virto'13].

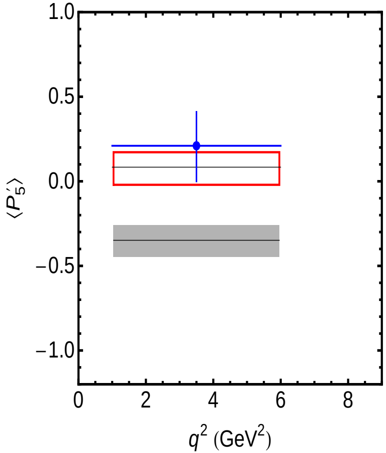
⇒ **Symmetries** among $A_{\perp,\|,0}$ [Egede, JM, Reece, Ramon'12] and [Serra, JM]

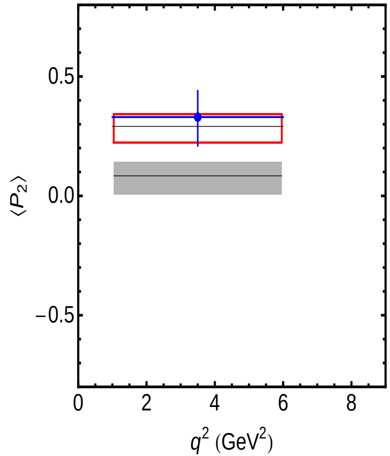
⇒ imply relations among the observables above.

In [DMV'13] it was shown that a New Physics contribution to the coefficient C_9: $C_9^{\rm NP} \sim -1.5$

reduced the tension on P_5', but also in P_2.



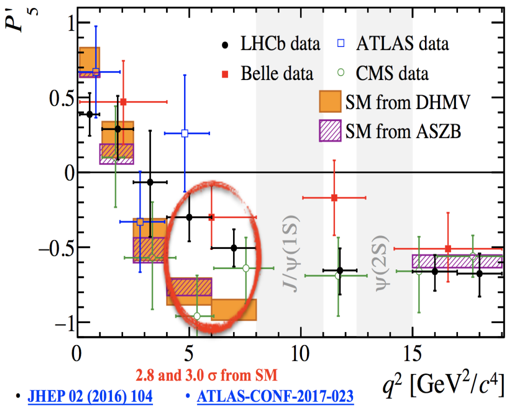




Gray: SM. Blue: LHCb data. Red: $C_9^{\rm NP}$.

P_5'.... a closer look to the most tested anomaly (Type-I)

Is this an statistical fluctuation?



- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

P_5' was proposed in **DMRV, JHEP 1301(2013)048**

$$P_5' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}} = P_5^\infty\left(1 + \mathcal{O}(\alpha_s \xi_\perp) + \text{p.c.}\right) .$$

Optimized Obs.: Soft form factor ($\xi_\perp$) cancellation at LO.

- 2013: 1fb^{-1} dataset LHCb found 3.7σ.
- 2015: 3fb^{-1} dataset LHCb (**black**) found 3σ in 2 bins.
  $\Rightarrow$ Predictions (**in orange**) from DHMV.
- Belle (**red**) confirmed it in a bin [4,8] few months ago.

Is there a problem with hadronic uncertainties?: Two robust and independent analysis (same as F_L):

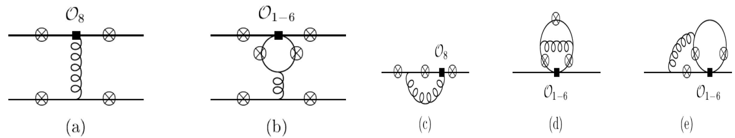
- ORANGE DHMV: using i-QCDF and KMPW FF+ 4 types of corrections.
- MAGENTA ASZB: using full FF from BSZ.

.... are in nice agreement and finds the anomaly.

P_5'.... a closer look to the most tested anomaly (Type-I)

$\boxed{1}$ Computed in i-QCDF + KMPW+ 4-types of corrections.

$$F^{full}(q^2) = F^{\infty}(\xi_\perp, \xi_\parallel) + \triangle F^{\alpha_s}(q^2) + \triangle F^{p.c.}(q^2) \qquad F^{full} = V, A_1, A_2, ...$$

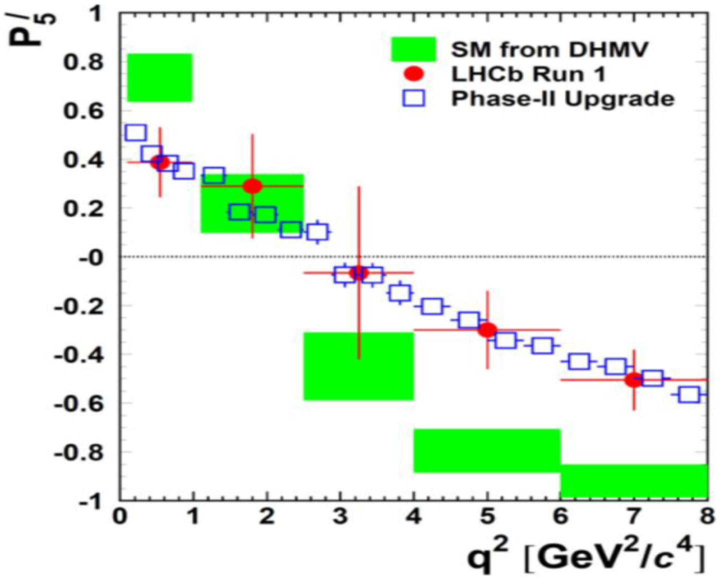
type of correction	Factorizable	Non-Factorizable
α_s-QCDF	$\triangle F^{\alpha_s}(q^2)$	
power-corrections	$\triangle F^{p.c.}(q^2)$*	LCSR with single soft gluon contribution (long distance charm)*

Why in P_5'?

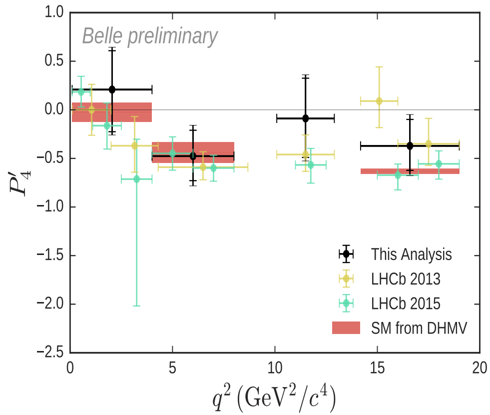
$$A^L_{\perp,\parallel,(0)} \propto \left[\mathcal{C}_9^{\rm eff} - \mathcal{C}_{10} + ...\right]\xi_{\perp,(\parallel)}(E_{K^*}) \qquad A^R_{\perp,\parallel,(0)} \propto \left[\mathcal{C}_9^{\rm eff} + \mathcal{C}_{10} + ...\right]\xi_{\perp,(\parallel)}(E_{K^*})$$

- In SM $\mathcal{C}_9^{SM} + \mathcal{C}_{10}^{SM} \simeq 0 \to |A^R_{\perp,\parallel}| \ll |A^L_{\perp,\parallel}|$
- If $C_9^{NP} < 0$ then R$\uparrow$ and L$\downarrow$: $P_5' \propto -{\rm Re}\left[|A_0^L A_\perp^{L*}| - |A_0^R A_\perp^{R*}|\right] \to 0$

Projections from LHCb for P_5' in Phase-II Upgrade. [Taken from LHCb]



Is it natural to see a deviation in P_5' and NOT in P_4'?



P_4' was proposed for the first time in **DMRV, JHEP 1301(2013)048**

$$P_4' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}} = P_4^\infty\left(1 + \mathcal{O}(\alpha_s \xi_\perp) + \mathrm{p.c.}\right).$$

Why not in P_4'?

$$A^L_{\perp,\parallel,(0)} \propto \left[\mathcal{C}_9^{\mathrm{eff}} - \mathcal{C}_{10} + \ldots\right]\xi_{\perp,(\parallel)}(E_{K^*}) \qquad A^R_{\perp,\parallel,(0)} \propto \left[\mathcal{C}_9^{\mathrm{eff}} + \mathcal{C}_{10} + \ldots\right]\xi_{\perp,(\parallel)}(E_{K^*})$$

- In SM $\mathcal{C}_9^{SM} + \mathcal{C}_{10}^{SM} \simeq 0 \to |A^R_{\perp,\parallel}| \ll |A^L_{\perp,\parallel}|$
- If $C_9^{NP} < 0$ then R$\uparrow$ and L$\downarrow$: $P_4' \propto \mathrm{Re}\left[|A_0^L A_\parallel^{L*}| + |A_0^R A_\parallel^{R*}|\right] \to P_4'^{\mathrm{SM}}$ what R gains L loses ...(unchanged).

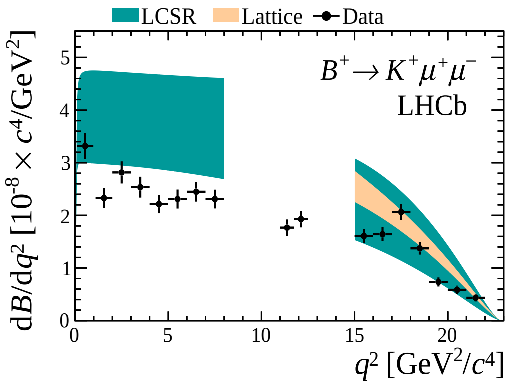
Systematic low-recoil small tensions (EXP too low compared with SM in several BR$_\mu$ also at large-recoil):

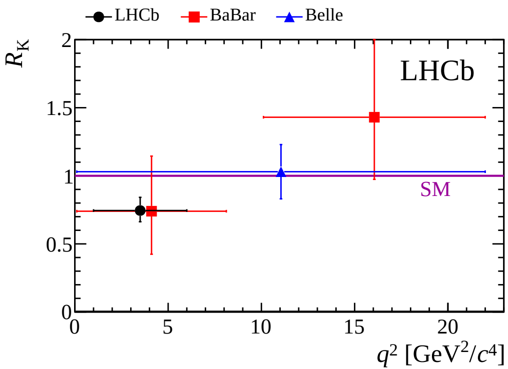
$b \to s\mu^+\mu^-$ (low-recoil)	bin	SM	EXP	Pull
$10^7 \times \mathrm{BR}(B^0 \to K^0\mu^+\mu^-)$	[15,19]	0.91 ± 0.12	0.67 ± 0.12	+1.4
$10^7 \times \mathrm{BR}(B^0 \to K^{*0}\mu^+\mu^-)$	[16,19]	1.66 ± 0.15	1.23 ± 0.20	+1.7
$10^7 \times \mathrm{BR}(B^+ \to K^{*+}\mu^+\mu^-)$	[15,19]	2.59 ± 0.25	1.60 ± 0.32	**+2.5**
$10^7 \times \mathrm{BR}(B_s \to \phi\mu^+\mu^-)$	[15,18.8]	2.20 ± 0.17	1.62 ± 0.20	**+2.2**

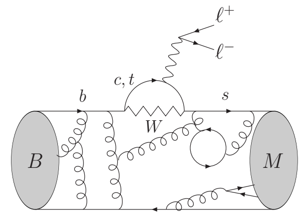
After including the BSZ DA correction that affected the error of twist-4:

$10^7 \times \mathrm{BR}(B_s \to \phi\mu^+\mu^-)$	SM	EXP	Pull
[0.1,2]	1.56 ± 0.35	1.11 ± 0.16	+1.1
[2,5]	1.55 ± 0.33	0.77 ± 0.14	**+2.2**
[5,8]	1.89 ± 0.40	0.96 ± 0.15	**+2.2**

In the meanwhile (2014) new deviations appear...LFUV anomalies







$$R_K = \frac{\mathrm{Br}\,(B^+ \to K^+ \mu^+ \mu^-)}{\mathrm{Br}\,(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$\Rightarrow$ It deviates $\mathbf{2.6}\sigma$ from SM.

$\Rightarrow$ equals to 1 in SM (universality of lepton coupling).

$\Rightarrow$ NP coupling $\neq$ to μ and e.

Conceptually R_K very relevant:

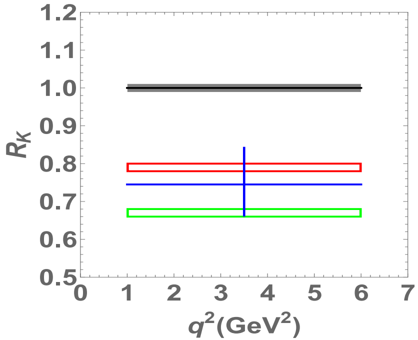
1. **Tensions in R_K cannot be explained in the SM by neither factorizable power corrections* nor long-distance charm*.**

LFUV (R_K) and $b \to s\mu^+\mu^-$ converges: (Coherence III)

$\boxed{1}$ The independent analysis of $b \to se^+e^-$ and $b \to s\mu^+\mu^-$ shows:

- $C_{9\mu} \sim -\mathcal{O}(1)$
- $C_{9e} \simeq 0$ compatible with SM albeit with large error bars.

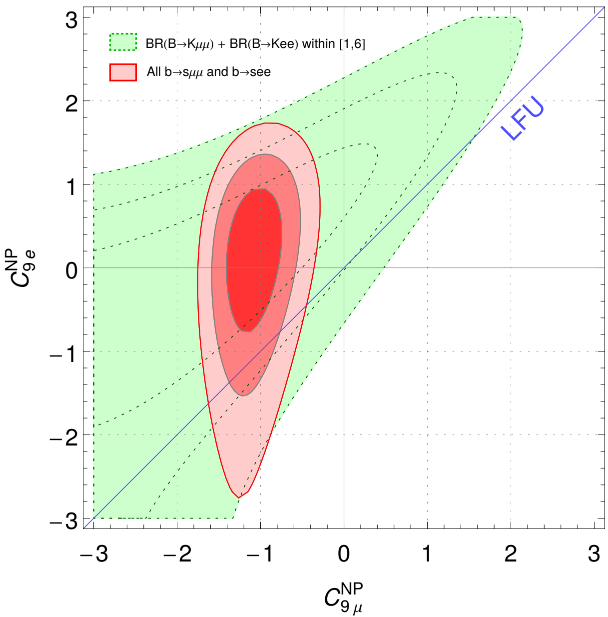
$\boxed{2}$ It shares the same explanation than P_5' and other $b \to s\mu\mu$ tensions.



$C_{9\mu}^{\rm NP} = -1.1, C_{9e}^{\rm NP} = 0$

and

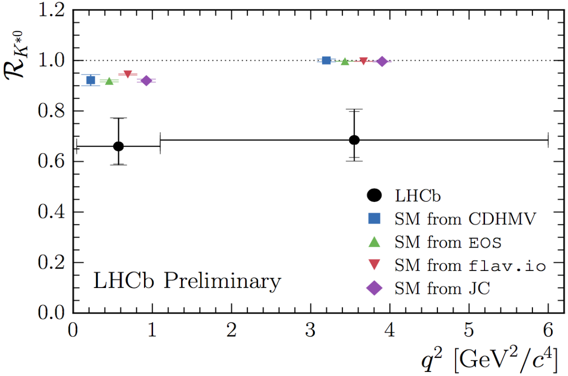
$C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.65$, $C_{9,10e}^{\rm NP} = 0$

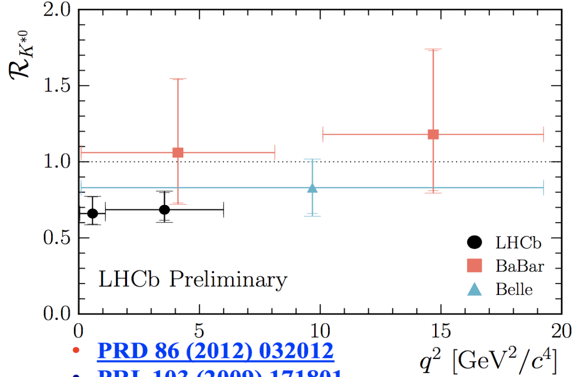


⇒ The attempts of explanation of anomalies in $b \to s\mu^+\mu^-$ based on hadronic arguments enter in crisis...

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

pulls	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
Exp.	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM	0.92 ± 0.02	1.00 ± 0.01





- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- Both R_K and R_{K^*} are very clean **but ONLY in the SM and for $q^2 \geq 1$ GeV^2**.
  - Lepton mass effects even in the SM are important in the first bin.
    $\rightarrow$ Our error size in 1st and 2nd bin in agreement with Isidori et al. (including QED $\rightarrow 0.03$).
- In presence of New Physics or for $q^2 < 1$ GeV^2 **hadronic uncertainties return.**
  - Typical wrong statement "R_{K,K^*} are ALWAYS very clean observable", indeed is substantially less clean and more FF dependent than any optimized observable.

What is the impact now

on the global fit of the new data?

[Capdevila, Crivellin, Descotes, JM, Virto]

175 observables in total (LHCb, Belle, ATLAS and CMS, no CP-violating obs)

- $B \to K^* \mu\mu$ ($P_{1,2}, P'_{4,5,6,8}, F_L$ in 5 large-recoil bins + 1 low-recoil bin)+available electronic observables.

...April's update of $\mathrm{Br}(B \to K^* \mu\mu)$ showing now a deficit in muonic channel.

...April's new result from LHCb on R_K^*

- $B_s \to \phi\mu\mu$ ($P_1, P'_{4,6}, F_L$ in 3 large-recoil bins + 1 low-recoil bin)
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\ell\ell$ (BR) ($\ell = e, \mu$) (R_K is implicit)
- $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$ (BR).
- Radiative decays: $B^0 \to K^{*0}\gamma$ (A_I and $S_{K^*\gamma}$), $B^+ \to K^{*+}\gamma$, $B_s \to \phi\gamma$

▶ New Belle measurements for the isospin-averaged but lepton-flavour dependent ($Q_{4,5} = P'^{\mu}_{4,5} - P'^{e}_{4,5}$):

$$P'^{\ell}_i = \sigma_+ \, P'^{\ell}_i(B^+) + (1-\sigma_+) \, P'^{\ell}_i(\bar{B}^0)$$

▶ New ATLAS and CMS measurements on P_i.

Fit 2016: Statistical Approach

Frequentist approach: $\mathcal{C}_i = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$, with $\mathcal{C}_i^{NP}$ assumed to be real (no CPV)

$$\chi^2(C_i) = [O_{\text{exp}} - O_{\text{th}}(C_i^{NP})]_j \, [Cov^{-1}]_{jk} \, [O_{\text{exp}} - O_{\text{th}}(C_i^{NP})]_k$$

- $\mathbf{Cov} = \mathbf{Cov}^{\text{exp}} + \mathbf{Cov}^{\text{th}}$.
- Calculate Cov^{th}: correlated multigaussian scan over all nuisance parameters
- Cov^{th} depends on C_i^{NP}: Must check this dependence

For the Fit:

- Minimise $\chi^2 \to \chi^2_{\text{min}} = \chi^2(C_i^{NP\,0})$ (Best Fit Point = $C_i^{NP\,0}$)
- Confidence level regions: $\chi^2(C_i^{NP}) - \chi^2_{\text{min}} < \Delta\chi_{\sigma,n}$

Definition of Pull$_{SM}$:

Pull$_{SM}$: how much the SM is disfavoured with respect to a New Physics hypothesis to explain data.
$\to$ A scenario with a large SM-pull $\Rightarrow$ big improvement over SM and better description of data.

Results: 1D fits: All $b \to s\ell\ell$ and LFUV fit

- Hypotheses "NP in some $\mathcal{C}_i$ only" (1D, 2D, 6D) to be compared with SM

	All				
1D Hyp.	Best fit	1 σ	2 σ	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	**-1.11**	$[-1.28, -0.94]$	$[-1.45, -0.75]$	5.8	68
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.62	$[-0.75, -0.49]$	$[-0.88, -0.37]$	5.3	58
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9\mu}'$	-1.01	$[-1.18, -0.84]$	$[-1.34, -0.65]$	5.4	61
$\mathcal{C}_{9\mu}^{\rm NP} = -3\mathcal{C}_{9e}^{\rm NP}$	-1.07	[-1.24,-0.90]	[-1.40,-0.72]	5.8	70

	LFUV				
1D Hyp.	Best fit	1 σ	2 σ	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.76	$[-2.36, -1.23]$	$[-3.04, -0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.66	$[-0.84, -0.48]$	$[-1.04, -0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9\mu}'$	-1.64	$[-2.13, -1.05]$	$[-2.52, -0.49]$	3.2	32
$\mathcal{C}_{9\mu}^{\rm NP} = -3\mathcal{C}_{9e}^{\rm NP}$	-1.35	$[-1.82, -0.95]$	$[-2.38, -0.59]$	4.0	72

Global fit test the ***coherence*** *of a set of deviations with a NP hypothesis versus SM hypothesis*

The 1D solution solves many anomalies and alleviates other tensions

Largest pulls	$\langle P_5'\rangle^{[4,6]}$	$\langle P_5'\rangle^{[6,8]}$	$\mathcal{B}^{[2,5]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[5,8]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[15,19]}_{B^+\to K^{*+}\mu^+\mu^-}$
Experiment	-0.30 ± 0.16	-0.51 ± 0.12	0.77 ± 0.14	0.96 ± 0.15	1.60 ± 0.32
SM pred.	-0.82 ± 0.08	-0.94 ± 0.08	1.55 ± 0.33	1.88 ± 0.39	2.59 ± 0.25
Pull (σ)	**-2.9**	**-2.9**	**+2.2**	**+2.2**	**+2.5**
Pred. $\mathcal{C}_{9\mu}^{\rm NP}=-1.1$	-0.50 ± 0.11	-0.73 ± 0.12	1.30 ± 0.26	1.51 ± 0.30	2.05 ± 0.18
Pull (σ)	**-1.0**	**-1.3**	**+1.8**	**+1.6**	**+1.2**

Largest pulls	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
Experiment	$0.745^{+0.097}_{-0.082}$	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM pred.	1.00 ± 0.01	0.92 ± 0.02	1.00 ± 0.01
Pull (σ)	**+2.6**	**+2.3**	**+2.6**
Pred. $\mathcal{C}_{9\mu}^{\rm NP}=-1.1$	0.79 ± 0.01	0.90 ± 0.05	0.87 ± 0.08
Pull (σ)	**+0.4**	**+1.9**	**+1.2**

.... we will come back to that later on.

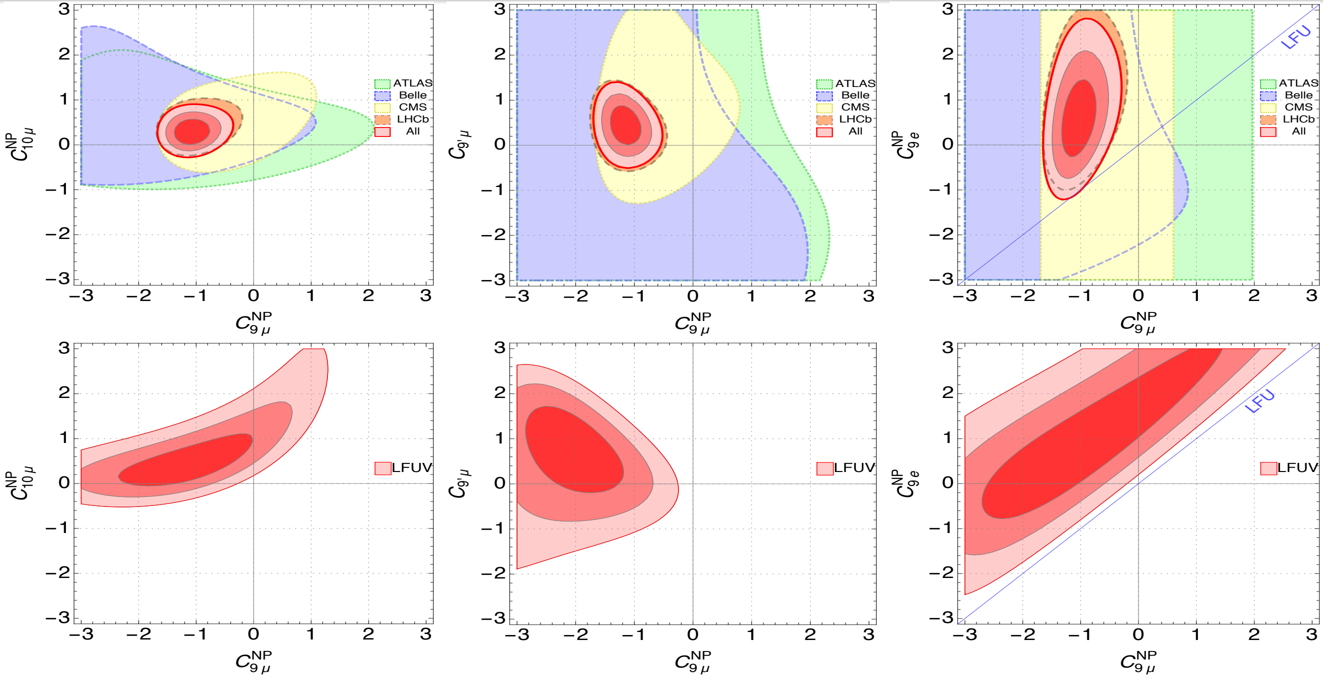
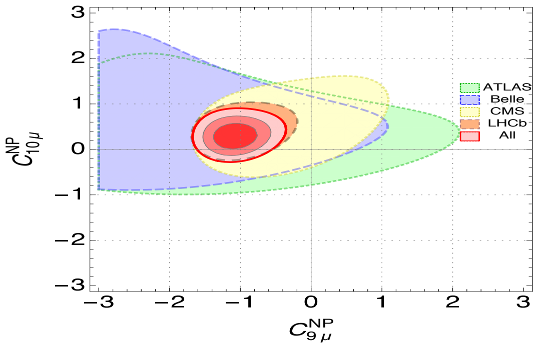
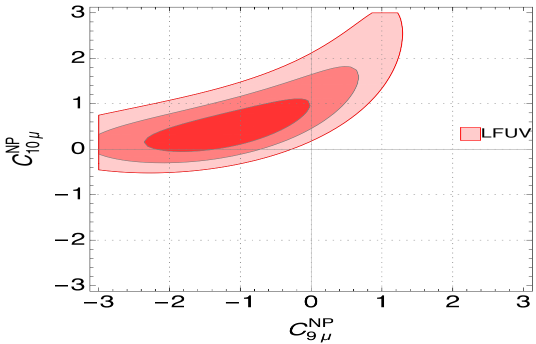


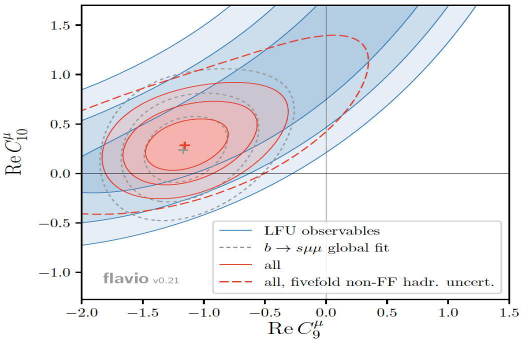
Figure: Allowed regions with all available data (upper) and only LFUV (lower) in good agreement. Constraints from $b \to s\gamma$ observables, $\mathcal{B}(B \to X_s\mu\mu)$ and $\mathcal{B}(B_s \to \mu\mu)$ always included. Experiments at 3σ.

Consistency with another analysis





[Capdevila, Crivellin, SDG, Matias, Virto]



[Altmannshofer, Stangl, Straub]

- Different angular observables
- Different form factor inputs (BSZ)
- Different treatment of hadronic corrections (full-FF)
- Same NP scenarios favoured (higher significances for [Altmannshofer, Stangl, Straub])

6D fit the most important one

We take all Wilson coefficients SM-like and chirally flipped as free parameters:
(neglect scalars and tensor operators)

	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Best fit	+0.03	-1.12	+0.31	+0.03	+0.38	+0.02
1 σ	$[-0.01, +0.05]$	$[-1.34, -0.88]$	$[+0.10, +0.57]$	$[+0.00, +0.06]$	$[-0.17, +1.04]$	$[-0.28, +0.36]$
2 σ	$[-0.03, +0.07]$	$[-1.54, -0.63]$	$[-0.08, +0.84]$	$[-0.02, +0.08]$	$[-0.59, +1.58]$	$[-0.54, +0.68]$

The SM pull moved from 3.6 σ → 5.0 σ (fit "All' with the latest CMS data at 8 TeV included)

The pattern (very similar to DHMV15):

$$\mathcal{C}_7^{\rm NP} \gtrsim 0,\ \mathcal{C}_{9\mu}^{\rm NP} < 0,\ \mathcal{C}_{10\mu}^{\rm NP} > 0,\ \mathcal{C}_7' \gtrsim 0,\ \mathcal{C}_{9\mu}' > 0,\ \mathcal{C}_{10\mu}' \gtrsim 0$$

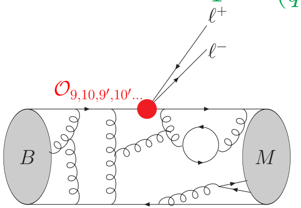
$\mathcal{C}_{9\mu}$ is compatible with the SM much beyond 3 σ, all the other coefficients at 1-2 σ.

Intermezzo... hadronic uncertainties on a nutshell. Are they an alternative?

There have been some **attempts** by a few groups to try to explain **a subset of** the previous **anomalies** using two arguments:

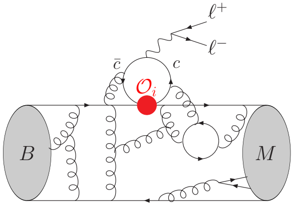
- factorizable power corrections (FPP) (**easy to discard arg (see back-up)**)

$$F^{full}(q^2) = F^{\infty}(\xi_\perp, \xi_\parallel) + \triangle F^{\alpha_s}(q^2) + \triangle F^{p.c.}(q^2) \qquad F^{full} = V, A_1, A_2, ...$$



- They have to be included in a correct way.
- Emphatic claims by one group of large impact of FPP but important missing points identified:
  - **scheme choice** inflates artificially error x4 if p.c. are taken uncorrelated.
  - a **correct** P_5' expansion in p.c shows explicitly scheme dependence.
  - **DHMV included them and also BSZ (full-FF) and results agree.**

- or unknown charm contributions... (**more difficult to discard but also possible with a global view**)



A detailed explanation of where those "'explanations" fails in [JHEP 1412 (2014) 125, JHEP 1704 (2017) 016]

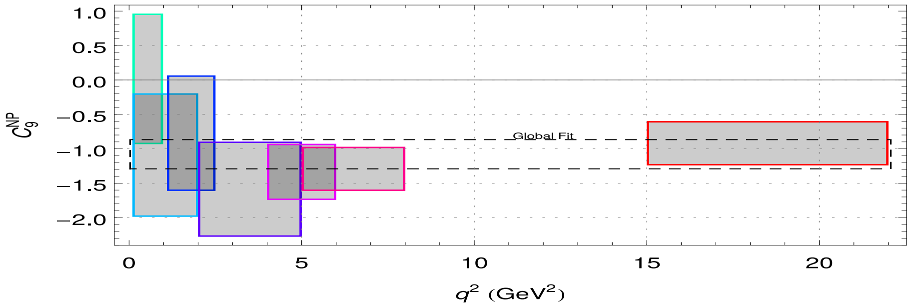
Problem: Charm-loop yields q^2- and hadronic-dependent contribution with $O_{7,9}$ structures that may mimic New Physics.

$$C_{9i}^{\rm eff}(q^2) = C_{9\,\rm SMpert} + C_9^{\rm NP} + \mathbf{C_{9i}^{c\bar{c}}(q^2)}. \qquad \mathbf{i} = \perp, \parallel, \mathbf{0}$$

How to disentangle? Is our long-dist $c\bar{c}$ estimate using KMPW as order of magnitude correct?

$\boxed{1}$ Fit to C_9^{NP} bin-by-bin of $b \to s\mu\mu$ data:

- NP is universal and q^2-independent.
- Hadronic effect associated to $c\bar{c}$ dynamics is (likely) q^2-dependent.



- The excellent agreement of bins [2,5], [4,6], [5,8]: $C_9^{NP\,[2,5]} = -1.6 \pm 0.7$, $C_9^{NP\,[4,6]} = -1.3 \pm 0.4$, $C_9^{NP\,[5,8]} = -1.3 \pm 0.3$ shows **no indication of** **<u>additional</u>** q^2- **dependence.**

A controversial point and its evolution... a long story in short

[Ciuchini et al.] introduced a second-order polynomial in amplitudes to parametrize $C_{9i}^{c\bar{c}}(q^2)$ and fitted the $h_i^{(K)}$ ($i = \perp, \|, 0$ and $K = 0, 1, 2$). Example:

$$A^0_{L,R} = A^0_{L,R}(Y(q^2)) + \frac{N}{q^2}\left(\underset{\mathbf{C_7}}{h_0^{(0)}} + \frac{q^2}{1\mathrm{GeV}^2}\underset{\mathbf{C_9}}{h_0^{(1)}} + \frac{q^4}{1\mathrm{GeV}^4}\mathbf{h_0^{(2)}}\right)$$

This group presented **a fit** (not a computation) in 1512.07157 only to large-recoil data of $B \to K^*\mu^+\mu^-$:

- v1: Symmetries proved an internal incoherence of their results for some observables above 4σ.
  $\rightarrow$ acknowledged by these authors.

- v2: insisted on presence of sizable nonfactorizable p.c. (in particular a nonvanishing $h_-^{(2)}$), which disfavours their interpretation as a shift of the SM Wilson coefficients at more than 95.45% prob.

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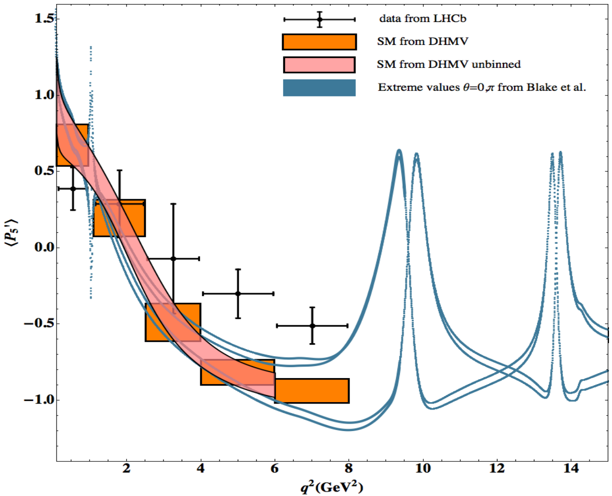
- v2: insisted on presence of sizable nonfactorizable p.c. (in particular a nonvanishing $h_-^{(2)}$), which disfavours their interpretation as a shift of the SM Wilson coefficients at more than 95.45% prob.
- Later on [1611.04338] same authors agreed that the solution with $h^{(2)} = 0$ gives an acceptable fit.
  $\to$ ... maybe there is an unknown constant hadronic contribution $h_-^{(1)}$ that mimics NP.

Long distance charm

More arguments to discard long distance charm as a solution.

- We implemented [JHEP 1704 (2017) 016] different analysis: SM, NP, different FFs,...⇒
No significant improvement in the quality of the fit that pointed to the need to go beyond the $h_\lambda^{(1)}$ term.

- Empirical model of long distance contributions based on the use of data on final states involving $J^{\mathrm{PC}} = 1^{--}$ resonances
⇒ Agreement with our error estimate.
⇒ Anomaly cannot be explained.



Moreover R_K^* was measured.... crisis of long-distance charm arguments!

From Mauro Valli's talk of Silvestrini et al. group.

NOT SO LONG TIME BACK ...

[Ciuchini et al'15] "SM gives a very good description of data and h_-^2 near 2σ from 0."

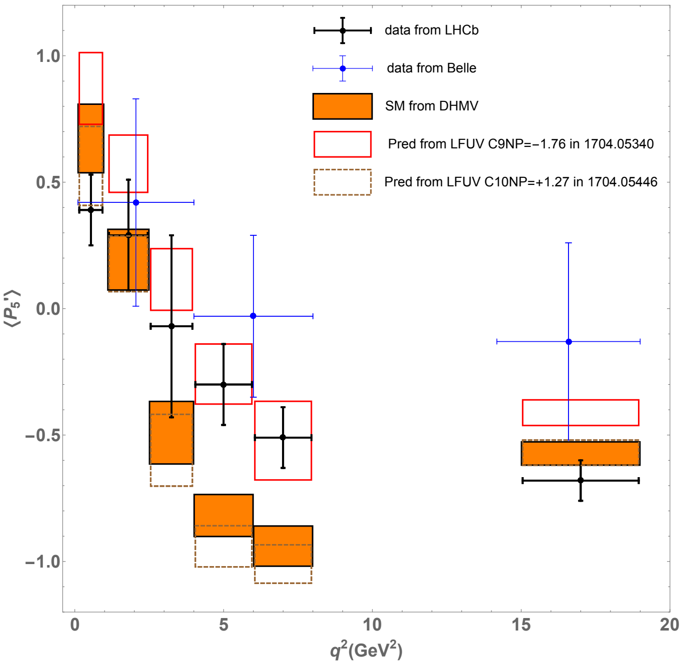
[Ciuchini et al'17] in unconstrained fit find up to 7σ on C_9^{NP} even missing low-recoil! and $h_\lambda^{(1,2)}$ now compatible with 0. **Alternative NP solution C_{10}^e proposed unable to explain any Type-I.**

Experiment: Assume ONLY LFUV observables are measured: R_K, R_{K^*} and $Q_{4,5}$

Question: What they predict for P_5'?

Three cases:

- $C_{9\mu} = -1.76$ (RED) from our paper 1704.05340.
- $C_{10\mu} = +1.27$ (BROWN) from 1704.05446.
- NP in $C_{10e} \Rightarrow$ as bad as SM (ORANGE)



but also improve on many other anomalies....:

Largest pulls	$\langle P_5' \rangle^{[4,6]}$	$\langle P_5' \rangle^{[6,8]}$	$\mathcal{B}^{[2,5]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[5,8]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[15,19]}_{B^+\to K^{*+}\mu^+\mu^-}$
Experiment	-0.30 ± 0.16	-0.51 ± 0.12	0.77 ± 0.14	0.96 ± 0.15	1.60 ± 0.32
SM pred.	-0.82 ± 0.08	-0.94 ± 0.08	1.55 ± 0.33	1.88 ± 0.39	2.59 ± 0.25
Pull (σ)	**-2.9**	**-2.9**	**+2.2**	**+2.2**	**+2.5**
Pred. $\mathcal{C}_{9\mu}^{\rm NP} = -1.76$	-0.26 ± 0.12	-0.52 ± 0.15	1.22 ± 0.22	1.37 ± 0.25	1.54 ± 0.10
Pull (σ)	**+0.2**	**-0.1**	**+1.7**	**+1.4**	**-0.3**

Largest pulls	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
Experiment	$0.745^{+0.097}_{-0.082}$	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM pred.	1.00 ± 0.01	0.92 ± 0.02	1.00 ± 0.01
Pull (σ)	**+2.6**	**+2.3**	**+2.6**
Pred. $\mathcal{C}_{9\mu}^{\rm NP} = -1.76$	0.69 ± 0.01	0.89 ± 0.09	0.83 ± 0.14
Pull (σ)	**-0.7**	**+1.6**	**+0.8**

Next step: Disentangling scenarios.

A glance into the future.

Looking into the near future: New LFUV to come (Disentangling)

Observables sensitive to the difference between $b \to s\mu\mu$ and $b \to see$:

$\boxed{1}$ They cannot be explained by neither factorizable power corrections nor long-distance charm.

$\boxed{2}$ They share same explanation than P_5' anomaly, assuming NP in e-mode is suppressed (OK with fit).

- Other ratios of Branching Ratios

$$R_\phi = \frac{\mathrm{BR}(B_s \to \phi\mu\mu)}{\mathrm{BR}(B_s \to \phi ee)}$$

- Difference of Optimized observables:
  $Q_i = P_i^\mu - P_i^e$.

  [CDMV'16]

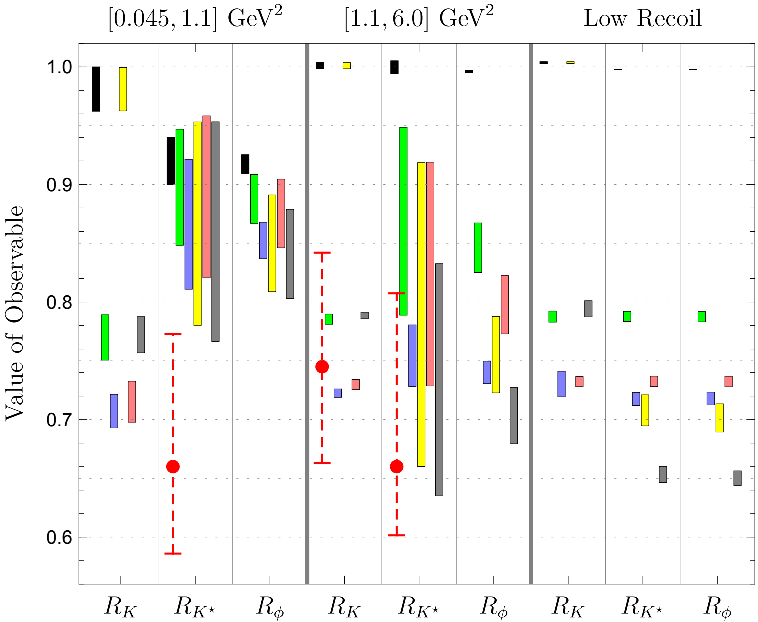
  $\to$ Inheritate the excellent properties of optimized observables

- Ratios of coefficients of angular distribution.
  $B_i = J_i^\mu / J_i^e - 1$ with i=5,6s.

- Ratios of non-optimized observables
  $T_i = \frac{S_i^\mu - S_i^e}{S_i^\mu + S_i^e}$

All are useful to find deviations from SM with tiny uncertainty, but to disentangle different NP scenarios Q_i and B_i (maybe T_i) are key observables.

Disentangling New Physics: Ratios of Branching Ratios



SM-[BLACK]

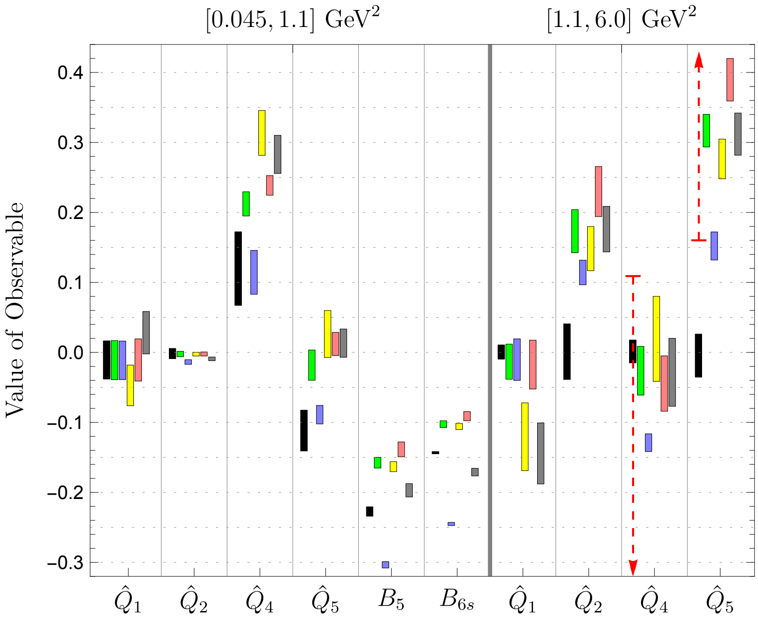
Five “good” scenarios:

- Sc. 1 [GREEN]: $C_{9\mu}^{\rm NP} = -1.1$,
- Sc. 2 [BLUE]: $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.61$,
- Sc. 3 [YELLOW]: $C_{9\mu}^{\rm NP} = -C'_{9\mu} = -1.01$,
- Sc. 4 [ORANGE]: $C_{9\mu}^{\rm NP} = -3C_{9e}^{\rm NP} = -1.06$,
- Sc. 5:[GRAY]: The best fit point in the six-dimensional fit.

R_{K^*} is computed using very conservative KMPW-FF but R_ϕ using BSZ-FF (only available).

ATTENTION: In presence of NP $R_{K,K^*,\phi}$ are largely sensitive to FF choices

Q_i observables are better to disentangle NP: Q_i inheritates the properties of optimized observables.



$$Q_i = P_i^\mu - P_i^e$$

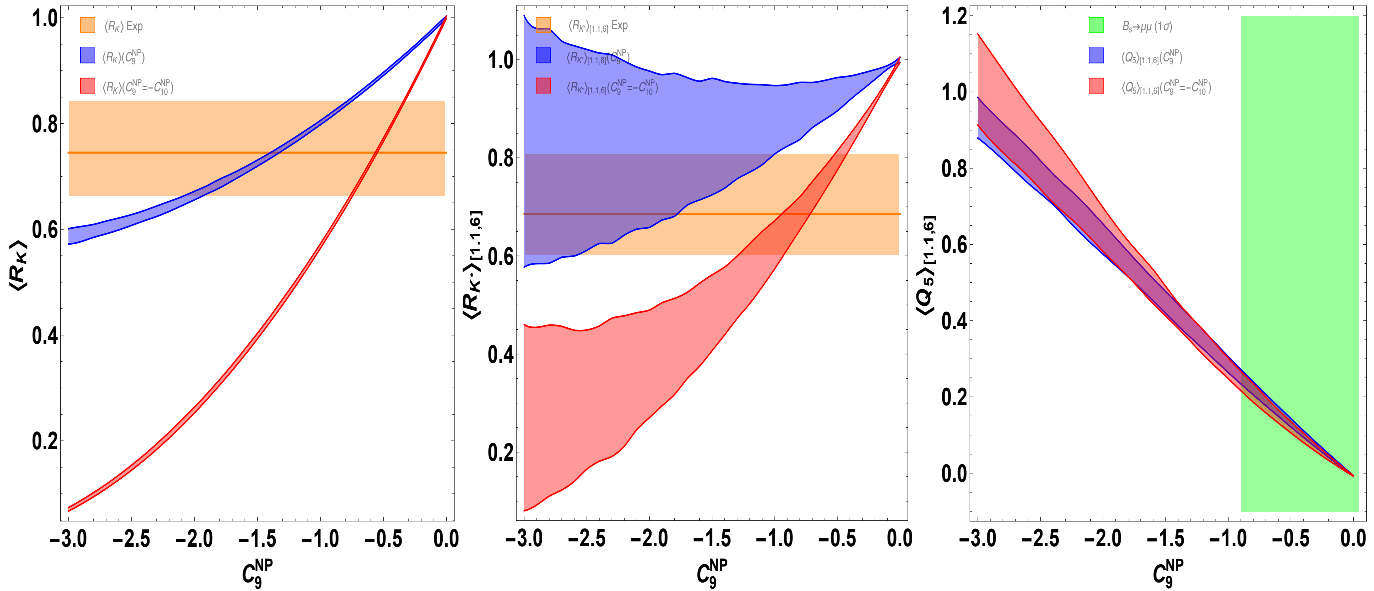
SM-[BLACK] and dashed-red [BELLE data]

Five “good” scenarios:

- Sc. 1 [GREEN]: $C_{9\mu}^{\rm NP} = -1.1$,
- Sc. 2 [BLUE]: $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.61$,
- Sc. 3 [YELLOW]: $C_{9\mu}^{\rm NP} = -C'_{9\mu} = -1.01$,
- Sc. 4 [ORANGE]: $C_{9\mu}^{\rm NP} = -3C_{9e}^{\rm NP} = -1.06$,
- Sc. 5:[GRAY]: The best fit point in the six-dimensional fit.

A precise measurement of Q_5 in [1,6] can discard the solution $C_9 = -C_{10}$ in front of all other sols.

Which LFUV observable can disentangle better the scenarios?



BLUE $C_9^{\rm NP}$ and RED $C_9^{\rm NP}=-C_{10}^{\rm NP}$, GREEN $B_s\to\mu^+\mu^-$ constraint

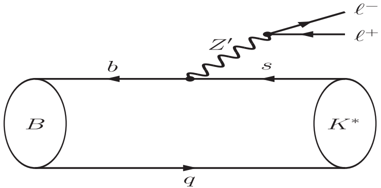
- Central value of R_K prefers a more negative contribution to $C_9^{\rm NP}$ in agreement with P_5'.
- A combined analysis of R_K and Q_5 may be enough constraining to disentangle the two scenarios: (present) $R_K \Rightarrow Q_5\in[0.60,0.25]$ favours $C_9^{\rm NP}$ or $Q_5\in[0.25,0.05]$ favours $C_9^{\rm NP}=-C_{10}^{\rm NP}$

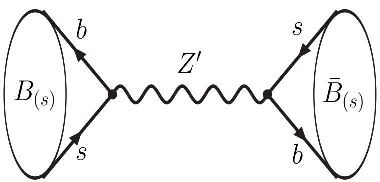
A Z' particle a possible explanation?

In [**DMV'13**] we proposed to explain the anomaly in $B \to K^* \mu\mu$ with a Z' **gauge boson** contributing to

$$\mathcal{O}_9 = e^2/(16\pi^2)\,(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$

with specific couplings as a possible explanation of the anomaly in P_5'.





$$\mathcal{L}^q = \left(\bar{s}\gamma_\nu P_L b \Delta_L^{sb} + \bar{s}\gamma_\nu P_R b \Delta_R^{sb} + h.c.\right) Z'^\nu \quad \mathcal{L}^{lep} = \left(\bar{\mu}\gamma_\nu P_L \mu {\Delta_{\mathbf{L}}}^{\mu\bar{\mu}} + \bar{\mu}\gamma_\nu P_R \mu {\Delta_{\mathbf{R}}}^{\mu\bar{\mu}} + ...\right) Z'^\nu$$

The Wilson coefficients of the semileptonic operators are:

$$\mathcal{C}^{\rm NP}_{\{9,10\}} = -\frac{1}{s_W^2 g_{SM}^2}\frac{1}{M_{Z'}^2}\frac{\Delta_L^{sb}\Delta^{\mu\mu}_{\{\mathbf{V},\mathbf{A}\}}}{\lambda_{ts}}\,, \quad \mathcal{C}^{\rm NP}_{\{9',10'\}} = -\frac{1}{s_W^2 g_{SM}^2}\frac{1}{M_{Z'}^2}\frac{\Delta_R^{sb}\Delta^{\mu\mu}_{\{\mathbf{V},\mathbf{A}\}}}{\lambda_{ts}}\,,$$

with the vector and axial couplings to muons: $\Delta^{\mu\mu}_{\mathbf{V},\mathbf{A}} = \Delta^{\mu\mu}_{\mathbf{R}} \pm \Delta^{\mu\mu}_{\mathbf{L}}$.

Δ_L^{sb} with same phase as $\lambda_{ts} = V_{tb}V_{ts}^*$ (to avoid ϕ_s) like in MFV. Main constraint from ΔM_{B_s} ($\Delta^{sb}_{L,R}$).

To include LFUV the Z' has to couple differently to μ than e (small coupling)

A Z' model can belong basically to three main categories:

- A model that generates ONLY a contribution to C_9^μ: $\Delta_L^{sb} \neq 0$, $\Delta_V^{\mu\mu} \neq 0$. What size?

  $C_9^{\rm NP} = -1.1$, $\Delta_V^{\mu\mu}/M'_Z = -0.6$ TeV^{-1} and $\Delta_L^{bs}/M'_Z = 0.003$ TeV^{-1}

- A model that generates a contribution ONLY to $\mathcal{C}_9^\mu$ and $\mathcal{C}_{10}^\mu$ (**no**-right-handed quark coupling).

  Two subcases:

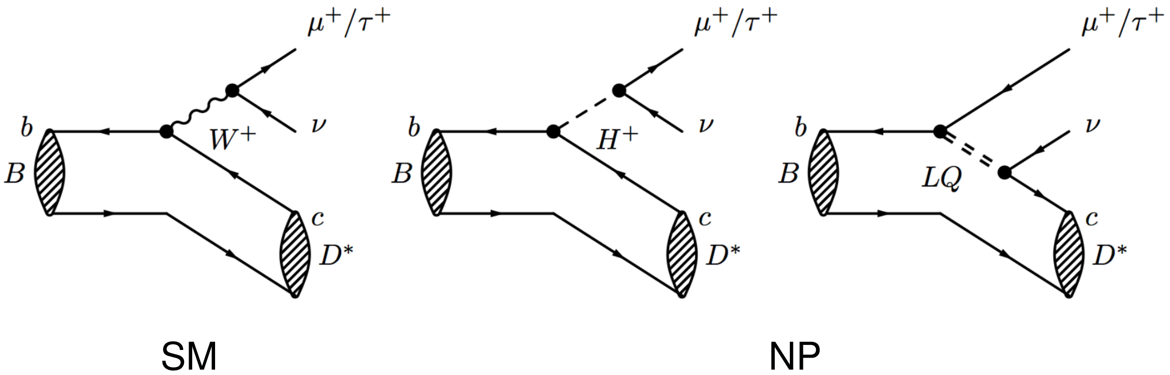
  - $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} \quad \Rightarrow \quad \Delta_L^{sb} \neq 0, \Delta_R^{\mu\mu} = 0$
  - $\mathcal{C}_9^{\rm NP} \neq 0, \mathcal{C}_{10}^{\rm NP} \neq 0 \quad \Rightarrow \quad \Delta_L^{sb} \neq 0, \Delta_V^{\mu\mu} \neq 0, \Delta_A^{\mu\mu} \neq 0$

- A model with contributions to all 4 Wilson coefficients $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$.

  In this case the constraint is particularly strong:

$$\mathcal{C}_9^{\rm NP}\,\mathcal{C}_{10'} - \mathcal{C}_{9'}\,\mathcal{C}_{10}^{\rm NP} = 0$$

Many ongoing attempts to embed this kind of Z' inside a model

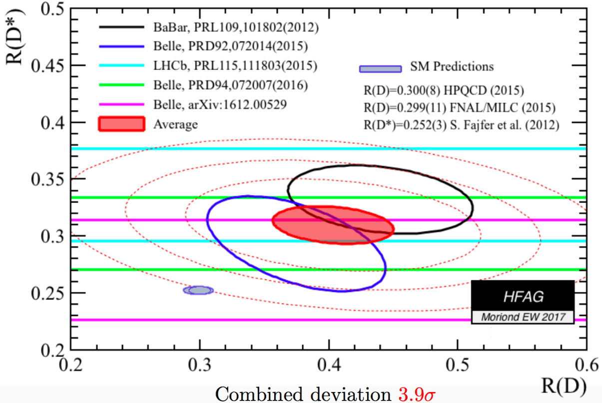


Semi-tauonic B decays are charged current processes that can probe also New Physics.
Experimentally (in analogy to R_{K,K^*}) a LFUV ratio:

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

The ratio:

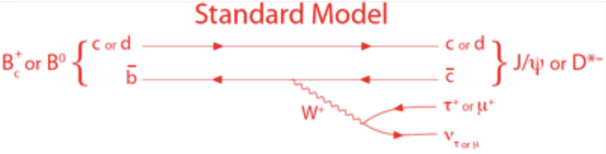
- differs in lepton mass: τ versus $\ell = \mu, e$ mass.
- cancels: form factors, V_{cb}, experimental systematics



Combined deviation 3.9σ

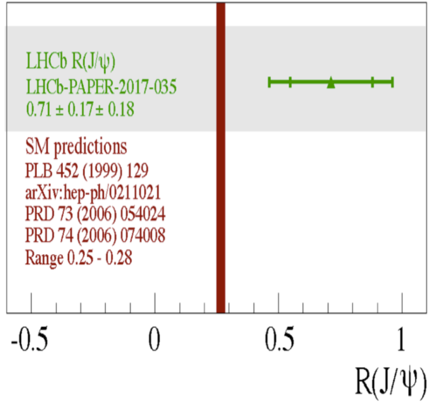
- Excess that becomes significant 3.9σ after combining experiments:
Babar and Belle ($\ell = \mu, e$), LHCb ($\ell = \mu$).
- Intriguing since this is a tree level process contrary to $b \to s\ell\ell$ related ones.

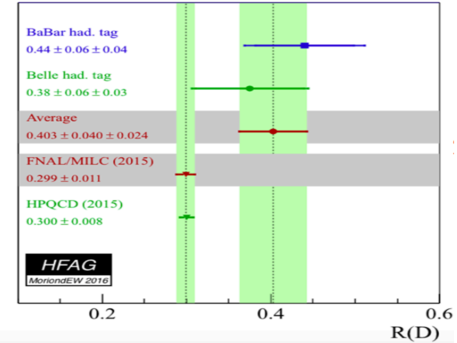
- **New evidence**



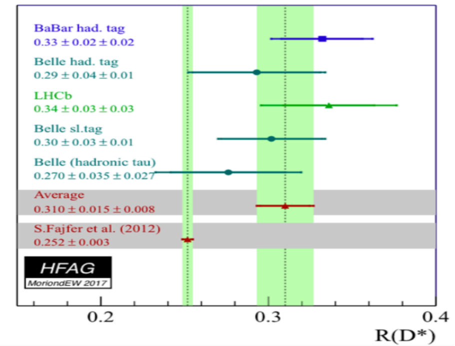
$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau \nu)}{\mathcal{B}(B_c^+ \to J/\psi \mu \nu)} = 0.71 \pm 0.17 \pm 0.18$$

(compatible with the SM at 2σ level)





- (HFAG) $R_D^{exp} = 0.403 \pm 0.040 \pm 0.024$
- Lattice computation of $B \to D$ FF: F^+, F^0 (precise).
- (FLAG 2016): 0.300 ± 0.008
- Latest SM prediction: combined fit HQET (incl. $\mathcal{O}(\Lambda/m_{c,b}, \alpha_s)$)+ measured $B \to D\ell\nu$ distributions together with LQCD and QCDSR inputs: $R_D^{SM} = 0.299 \pm 0.003$ ([Bernlochner et al.'17]) ($\mathbf{2.2}\sigma$)



- (HFAG) $R_{D^*}^{exp} = 0.310 \pm 0.015 \pm 0.008$ (more precise)
- Lattice computation of $B \to D^*$ FF: V, $A_{0,1,2}$, $T_{1,2,3}$. (no non-zero recoil LQCD)
- Latest SM prediction: combined fit HQET (incl. $\mathcal{O}(\Lambda/m_{c,b}, \alpha_s)$)+ measured $B \to D^*\ell\nu$ distributions together with LQCD and QCDSR inputs: $R_{D^*}^{SM} = 0.257 \pm 0.003$ ([Bernlochner et al.'17]) ($\mathbf{3.1}\sigma$)

$R(D^{(*)})$ $\Rightarrow$ 10% NP contribution in Amplitude of $B \to D^{(*)}\tau^+\nu$

Assuming a common NP explanation of R_D, R_{D^*} and $R_{J/\psi}$ (same change of norm. in G_F) such that

$$R_{J/\psi}/R_{J/\psi}^{\rm SM} = R_D/R_D^{\rm SM} = R_{D^*}/R_{D^*}^{\rm SM}$$

Hypothesis: NP at high scale, two SM-based $SU(2)_L$ invariant operators at dimension 6.

Constraints: EW precision data+direct searches
$+B \to K^{(*)}\nu\bar{\nu}$

$\Rightarrow b \to c\tau^-\nu_\tau$ and $b \to s\tau^+\tau^-$ generated together.

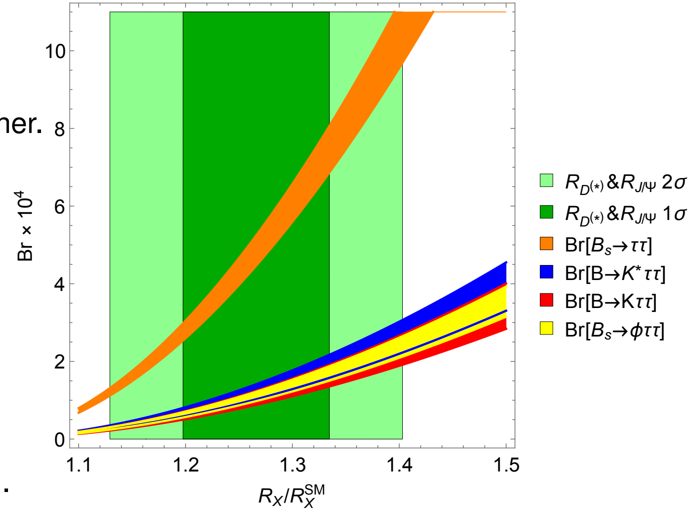
$$C_{9(10)\tau} \simeq C_{9,10}^{SM} - (+)\Delta$$

$$\Delta = 2\frac{\pi}{\alpha_{em}}\frac{V_{cb}}{V_{tb}V_{ts}^*}\left(\sqrt{\frac{R_X}{R_X^{SM}}} - 1\right) \simeq \mathcal{O}(100)$$

Consequently

$$\mathcal{B}^{\rm SM}_{B_s\to\tau^+\tau^-} \sim 10^{-7} \to \mathcal{B}_{B_s\to\tau^+\tau^-} \sim 10^{-4}$$

also $\mathcal{B}_{B\to K\tau^+\tau^-}$, $\mathcal{B}_{B\to K^*\tau^+\tau^-}$, $\mathcal{B}_{B_s\to\phi\tau^+\tau^-}$ all $\propto \Delta^2$.



Scale of New physics

Flavour observables are sensitive to higher scales than direct searches at colliders

... if NP affects flavour it is not surprising that we detect it first.

What is the scale of NP for $b \to s\ell\ell$? Reescaling the Hamiltonian by $H_{eff}^{\rm NP} = \sum \frac{\mathcal{O}_i}{\Lambda_i^2}$

- Tree-level induced (semi-leptonic) with $\mathcal{O}(1)$ couplings ($\times\sqrt{g_{bs}\, g_{\mu\mu}}$):

$$\Lambda_i^{\rm Tree} = \frac{4\pi v}{s_w g} \frac{1}{\sqrt{2|V_{tb}V_{ts}^*|}} \frac{1}{|C_i^{\rm NP}|^{1/2}} \sim \frac{35 {\rm TeV}}{|C_i^{\rm NP}|^{1/2}}$$

- Loop level-induced (semi-leptonic) with $\mathcal{O}(1)$ couplings:

$$\Lambda_i^{\rm Loop} \sim \frac{35 {\rm TeV}}{4\pi|C_i^{\rm NP}|^{1/2}} = \frac{2.8 {\rm TeV}}{|C_i^{\rm NP}|^{1/2}}$$

- MFV with CKM-SM, extra suppression $\sqrt{|V_{tb}V_{ts}^*|} \sim 1/5$

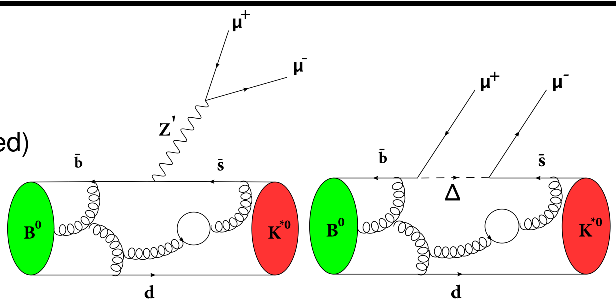
Solution $C_9^{\rm NP} \sim -1.1$ (scale is $\sim$ numerator) or $C_9^{\rm NP} = -C_{10}^{\rm NP} \sim -0.6$ (30 % higher scale).

Similar exercise for $b \to c\tau\nu$ taking a 10% (in amplitude) enhancement over SM:

$$\Lambda^{\rm NP} \sim 1/(\sqrt{2}G_F|V_{cb}|0.10)^{1/2} \sim 3.9\,{\rm TeV}$$

$b \to s\ell\ell$	$R(D) - R(D^*)$	a_μ
Z'	Charged scalars (problems with B_c lifetime)	Z'
Leptoquarks	Leptoquarks (strong impact on $qq \to \tau\tau$)	Leptoquarks
Loop effects	W' (fine-tunning required)	MSSM
Compositeness...	Compositeness...	Scalars

- Z' solution:
  - Heavy: LOOP (no FVQ coupling req.) and TREE (require FVQ couplings)
  - Light (easy to discard if low-recoil tensions confirmed)
- Leptoquarks solution:
  - Vector (Tree)
  - Scalar (Tree or Loop with a fermion)



Conclusions

- For the first time, we observe in particle physics a large set of coherent deviations in observables of rare B meson decays:

  $\boxed{1}$ in $b \to s\mu^+\mu^-$: P_5', $\mathcal{B}_{B^+\to K^{*+}\mu^+\mu^-}$, $\mathcal{B}_{B_s\to\phi\mu^+\mu^-}$ (low and large-recoil).

  $\boxed{2}$ in LFUV observables: R_K,R_{K^*}, $Q_{4,5}$

  pointing to different patterns/scenarios of NP:

  - $\mathcal{C}_{9\mu} = -1.1$, $\mathcal{C}_{9e} = 0$ with pull-SM 5.8σ
  - $\mathcal{C}_{9\mu} = -\mathcal{C}_{10\mu} = -0.62$, $\mathcal{C}_{9e} = 0$ with pull-SM 5.3σ
  - $\mathcal{C}_{9\mu} = -3\mathcal{C}_{9e} = -1.07$ with pull-SM 5.8σ

- Future LFUV observables, like Q_5 will have the discriminating power to disentangle some patterns $\to$ this will guide us in deciding the right model (or set of models).

- Semi-tauonic B decay anomalies $R_{D,D^*,J/\psi}$ under general assumptions maybe connected with enhanced (up to 3 orders of magnitude) $b \to s\tau^+\tau^-$ processes.

Now **really** exciting times are coming!!

THANK YOU!

BACK-UP

A complete basis of optimized observables

$$\mathbf{P_1} = \frac{J_3}{2J_{2s}} = \frac{|A_\perp|^2 - |A_\||^2}{|A_\perp|^2 + |A_\||^2} \qquad \mathbf{P_2} = \frac{J_{6s}}{8J_{2s}} = \frac{\mathrm{Re}[A_\perp^{L*} A_\|^L - A_\perp^R A_\|^{R*}]}{|A_\perp|^2 + |A_\||^2}$$

$$\mathbf{P_4'} = \frac{J_4}{\sqrt{-J_{2s}J_{2c}}} = \sqrt{2}\frac{\mathrm{Re}[A_0^L A_\|^{L*} + A_0^R A_\|^{R*}]}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\||^2)}} \qquad \mathbf{P_5'} = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}} = \sqrt{2}\frac{\mathrm{Re}[A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}]}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\||^2)}}$$

and the angular distribution:

$$\frac{1}{\Gamma'_{full}}\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}\mathbf{F_T}\sin^2\theta_K + \mathbf{F_L}\cos^2\theta_K + (\frac{1}{4}\mathbf{F_T}\sin^2\theta_K - \mathbf{F_L}\cos^2\theta_K)\cos 2\theta_l$$

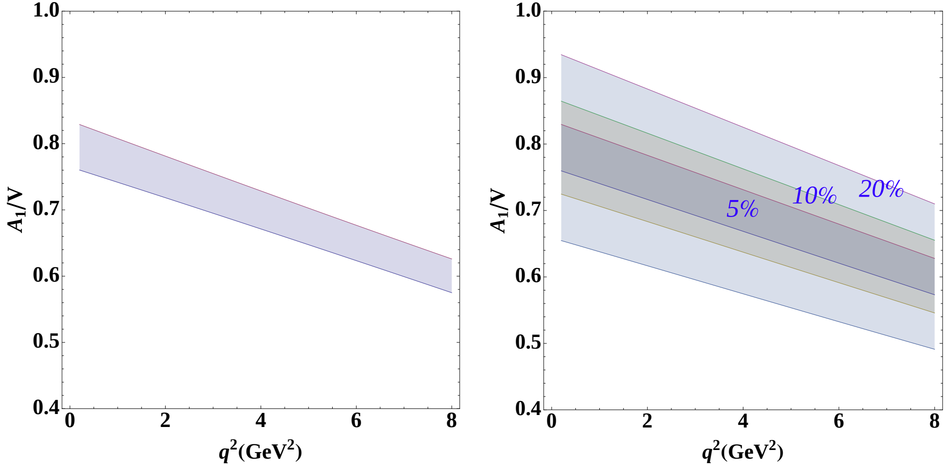
$$+\sqrt{\mathbf{F_T F_L}}\left(\frac{1}{2}\mathbf{P_4'}\sin 2\theta_K \sin 2\theta_l \cos\phi + \mathbf{P_5'}\sin 2\theta_K \sin\theta_l \cos\phi\right) + 2\mathbf{P_2 F_T}\sin^2\theta_K\cos\theta_l + \frac{1}{2}\mathbf{P_1 F_T}\sin^2\theta_K \sin^2\theta_l \cos 2\phi$$

$$-\sqrt{\mathbf{F_T F_L}}\left(\mathbf{P_6'}\sin 2\theta_K \sin\theta_l \sin\phi - \frac{1}{2}\mathbf{P_8'}\sin 2\theta_K \sin 2\theta_l \sin\phi\right) - \mathbf{P_3 F_T}\sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big](1 - \mathbf{F_S}) + \frac{1}{\Gamma'_{full}}\mathbf{W_S}$$

Folding: Identifying $\phi \leftrightarrow -\phi$ and $\theta_\ell \leftrightarrow \pi - \theta_\ell$ leads to

$$d\Gamma = d\Gamma(\hat\phi) + d\Gamma(-\hat\phi) + d\Gamma(\hat\phi, \pi - \hat\theta_\ell) + d\Gamma(-\hat\phi, \pi - \hat\theta_\ell) = \frac{9}{8\pi}\sqrt{F_T F_L}\,\mathbf{P_5'}\cos\hat\phi\,\sin 2\hat\theta_K\,\sin\hat\theta_\ell(1 - F_S) + \ldots$$

Compare the ratio A_1/V (that controls P_5') computed using BSZ (including correlations) and computed with our approach for different size of power corrections.



Assigning a 5% error (we take 10%) to the power correction error reproduces the full error of the full-FF!!!

Let's illustrate now points 1 and 2 with two examples.

Scheme-dependence (illustrative example-I)

Model independent ⟷ Full LCSR information

$\boxed{1}$

- ★ $\triangle F^{\rm PC} = F \times \mathcal{O}(\Lambda/m_B) \sim F \times 10\%$
- ★ **correlations** from large-recoil sym. $\rightarrow \xi_{\perp,\|}, \triangle F^{\rm PC}$ uncorr.

$\boxed{2}$

- ★ $\triangle F^{\rm PC}$ from fit to LCSR
- ★ **correlations** from large-recoil sym. $\rightarrow \xi_{\perp,\|}, \triangle F^{\rm PC}$ uncorr.

$\boxed{3}$

- ★ $\triangle F^{\rm PC}$from fit to LCSR
- ★ **correlations** from LCSR $\rightarrow \xi_{\perp,\|}, \triangle F^{\rm PC}$ corr.

$P_5'[4.0, 6.0]$	scheme 1 [CDHM]	scheme 2 [JC]
$\boxed{1}$	$-0.72 \pm \mathbf{0.05}$	$-0.72 \pm \mathbf{0.12}$
$\boxed{2}$	-0.72 ± 0.03	-0.72 ± 0.03
$\boxed{3}$	-0.72 ± 0.03	-0.72 ± 0.03
full BSZ	$-0.72 \pm \mathbf{0.03}$	

errors only from pc with BSZ form factors

[Capdevila, Descotes, Hofer, JM]

- [Bharucha, Straub, Zwicky] as example (correlation provided)
- scheme indep. restored if $\triangle F^{\rm PC}$ from fit to LCSR, with expected magnitude
- sensitivity to scheme can be understood analytically
- no uncontrolled large power corrections for $P_{5'}$

Correlations (illustrative example-II)

- How much I need to inflate the errors from factorizable p.c. to get 1-σ agreement with data for $P'_{5\,[4,6]}$ and $P_{1\,[4,6]}$ individually?

  $\star$ One needs near 40% p.c. for $P'_{5\,[4,6]}$ and 0% for $P_{1\,[4,6]}$.

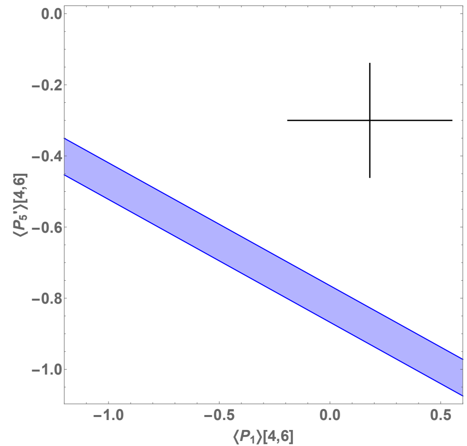
  $\star$ This would be in direct conflict with the two existing LCSR computations: KMPW and BSZ.

- But including the **strong correlation between p.c. of $P'_{5\,[4,6]}$ and $P_{1\,[4,6]}$ [CDHM] more than 60% ($> 80\%$ in bin [6,8]) is required!!!**

$$P'_5 = P'_5|_\infty \left(1 + \frac{2a_{V_-} - 2a_{T_-}}{\xi_\perp} \frac{C_7^{\rm eff}(C_{9,\perp}C_{9,\|} - C_{10}^2)}{(C_{9,\perp}+C_{9,\|})(C_{9,\perp}^2 + C_{10}^2)} \frac{m_b m_B}{q^2} - \frac{\mathbf{2a_{V_+}}}{\xi_\perp} \frac{\mathbf{C_{9,\|}}}{\mathbf{C_{9,\perp} + C_{9,\|}}} + \ldots\right.$$

$$P_1 = -\frac{\mathbf{2a_{V_+}}}{\xi_\perp} \frac{(\mathbf{C_9^{\rm eff} C_{9,\perp} + C_{10}^2})}{\mathbf{C_{9,\perp}^2 + C_{10}^2}} + \ldots$$

The leading term **in red** in P'_5 is missing in JC'14.



Summary of tensions/anomalies classified in two types

Type-I: Main anomalies currently observed in $b \to s\mu^+\mu^-$ transitions:

- Optimized observables: P_5'
- FFD observables: Systematic deficit of muonic modes at large and low-recoil of several BR

$$B \to K^*\mu^+\mu^-,\ B^+ \to K^{*+}\mu^+\mu^-,\ B_s \to \phi\mu^+\mu^-,\ B^{+,0} \to K^{+0}\mu^+\mu^-.$$

Largest pulls	$\langle P_5' \rangle_{[4,6]}$	$\langle P_5' \rangle_{[6,8]}$	$\mathcal{B}^{[2,5]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[5,8]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[15,18.8]}_{B_s\to\phi\mu^+\mu^-}$	$\mathcal{B}^{[15,19]}_{B^+\to K^{*+}\mu^+\mu^-}$
Exp.	-0.30 ± 0.16	-0.51 ± 0.12	0.77 ± 0.14	0.96 ± 0.15	1.62 ± 0.20	1.60 ± 0.32
SM	-0.82 ± 0.08	-0.94 ± 0.08	1.55 ± 0.33	1.88 ± 0.39	2.20 ± 0.17	2.59 ± 0.25
Pull (σ)	-2.9	-2.9	+2.2	+2.2	+2.2	+2.5

$\Rightarrow$ New Physics in muonic Wilson coefficients.

Type-II: Anomalies in LFUV observables: Ratios of BR ($B \to [P,V]\mu^+\mu^-$)/BR ($B \to [P,V]e^+e^-$).

Largest pulls	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
Exp.	$0.745^{+0.097}_{-0.082}$	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM	1.00 ± 0.01	0.92 ± 0.02	1.00 ± 0.01
Pull (σ)	+2.6	+2.3	+2.6

$\Rightarrow$ Hints that Nature does not treat electrons and muons in the same way (opposite to SM predictions).

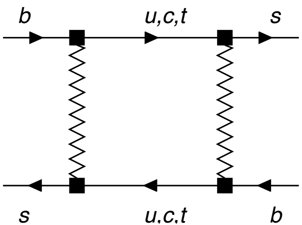
	Observable	New Physics in $\mu^\pm$	Hadronic option [Ciuchini, Silvestrini et al] + NP in $e^\pm$
a)	$\langle P_5' \rangle^{[4,6]}$	$C_9^{\rm NP} < 0$	Unknown hadronic ct. 1 and mimic NP (large-rec)
b)	$\langle P_5' \rangle^{[6,8]}$	same solution	Unknown hadronic ct. 1 and mimic NP (large-rec)
c)	$\mathcal{B}^{[15,19]}_{B^+\to K^{*+}\mu^+\mu^-}$	same solution	Unknown hadronic ct. 2 and mimic NP (low-rec)
d)	$\mathcal{B}^{[15,19]}_{B^+\to K^{+}\mu^+\mu^-}$	same solution	Unknown hadronic ct. 3 and mimic NP (low-rec)
e)	$\mathcal{B}^{[15,19]}_{B^0\to K^{0}\mu^+\mu^-}$	same solution	Unknown hadronic ct. 4 and mimic NP (low-rec)
f)	$\mathcal{B}^{[2,5]}_{B_s\to \phi\mu^+\mu^-}$	same solution	Unknown hadronic ct. 5 and mimic NP (large-rec)
g)	$\mathcal{B}^{[5,8]}_{B_s\to \phi\mu^+\mu^-}$	same solution	Unknown hadronic ct. 5 and mimic NP (large-rec)
h)	$\mathcal{B}^{[15,18]}_{B_s\to \phi\mu^+\mu^-}$	same solution	Unknown hadronic ct. 6 and mimic NP (low-rec)
i)	$R_K^{[1,6]}$	same solution	No Hadronic sol., NP C_{10}^e do not explain a-h
j)	$R_{K^*}^{[1,6]}$	same solution	No Hadronic sol., NP C_{10}^e do not explain a-h
k)	$Q_5^{[1,6]}$	same solution	No Hadronic sol., NP C_{10}^e do not explain a-h

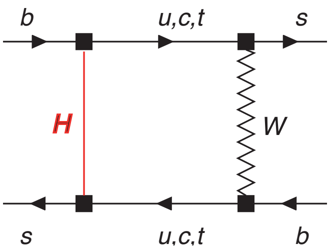
Summary: Hadronic solution to explain anomalies:

- Requires 6 different unknown $C_9^{\rm non-pert.}$ contributions (by hand)
- Impossible to explain R_K, R_{K^*} and Q_5.
- Alternative NP in electrons fail to explain all $b \to s\mu^+\mu^-$ anomalies

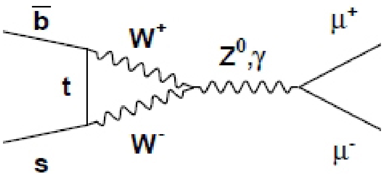
In SM, there are no FCNC processes present at the tree level due to the built-in GIM Mechanism so good place for NP to show up (tree or loops)

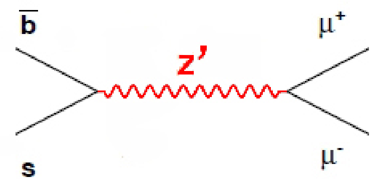
B_s mixing





$B_s \to \mu\mu$





Experimental and theoretical effort on interesting FCNC transitions

A controversial point and its evolution...a long story in short

[Ciuchini et al.] parametrized $C_{9i}^{c\bar{c}}(q^2)$ in amplitude and fitted the $h_i^{(K)}$ ($i = \perp, \|, 0$ and $K = 0, 1, 2$):

$$A^0_{L,R} = A^0_{L,R}(Y(q^2)) + \frac{N}{q^2}\left(h_0^{(0)} + \frac{q^2}{1\text{GeV}^2}h_0^{(1)} + \frac{q^4}{1\text{GeV}^4}h_0^{(2)}\right)$$

THIS IS A FIT to LHCb of only $B \to K^*\mu\mu$ large-recoil data NOT A COMPUTATION
They use BSZ-FF for predictions so form factors must no be an issue for them...

$\boxed{a}$ Unconstrained Fit finds constant contribution similar for all helicity-amplitudes.

- $\rightarrow$ In full agreement with our global fit.
- $\rightarrow$ Problem: They interpret this constant universal contribution as of unknown hadronic origin??
  Interestingly: the same constant also explains R_K ONLY if it is of NP origin and NOT if hadronic origin.

$\boxed{b}$ Constrained Fit: Imposing SM+ $C_{9i}^{c\bar{c}}$ (from KMPW) at $q^2 < 1$ GeV^2 is highly controversial:

- $\rightarrow$ arbitrary choice that tilts the fit, inducing spurious **large** q^4-dependence.
- $\rightarrow$ fit to first bin that misses the lepton mass approximation by LHCb
- $\rightarrow$ Imposing $Re[|C_{9i}^{c\bar{c}}|_{fitted}]^2 + Im[|C_{9i}^{c\bar{c}}|_{fitted}]^2 = Re[C_{9i}^{c\bar{c}}|_{KMPW}]^2 + Im[C_{9i}^{c\bar{c}}|_{KMPW}]^2$, is inconsistent since $Im[C_{9i}^{c\bar{c}}]$ was never computed in KMPW!!

Same authors have repeated their analysis but using more data besides $B \to K^*\mu^+\mu^-$ and the result...

$R(D^{(*)}) \Rightarrow$ 20% NP contribution in BR of $B \to D^{(*)}\tau^+\nu$

Constraints:

B_c lifetime and the q^2-contribution of $R(D^{(*)}) \to$ change of normalization of G_F for $b \to s\tau^+\tau^-$.

Hypothesis: NP at high scale, assume $SU(2)$ invariance, two SM-based operators at dimension 6:

$$\mathcal{O}^1 = \mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i\gamma_\mu Q_j][\bar{L}_k\gamma^\mu L_l], \quad \mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i\gamma_\mu\sigma^I Q_j][\bar{L}_k\gamma^\mu\sigma^I L_l]$$

after EWSB:

$$C^{(1)}_{23}\left([\bar{s}_L\gamma_\mu b_L][\bar{\tau}_L\gamma^\mu\tau_L] + [\bar{s}_L\gamma_\mu b_L][\bar{\nu}_\tau\gamma^\mu\nu_\tau]\right),$$
$$C^{(3)}_{23}\left(2V_{cs}[\bar{c}_L\gamma_\mu b_L][\bar{\tau}_L\gamma^\mu\nu_\tau] + [\bar{s}_L\gamma_\mu b_L][\bar{\tau}_L\gamma^\mu\tau_L] - [\bar{s}_L\gamma_\mu b_L][\bar{\nu}_\tau\gamma^\mu\nu_\tau]\right) + C^{(3)}_{33}\left(2V_{cb}[\bar{c}_L\gamma_\mu b_L][\bar{\tau}_L\gamma^\mu\nu_\tau]\right)$$

Problem+ Solution:

- NP contribution to $C^{(3)}_{33}$ with flavour-diagonal alignment to 3rd generation.
  Problem: Too large $C^{(3)}_{3,3}$ conflict with electroweak precision data + direct searches.
- NP contribution to $C^{(1,3)}_{23}$ produce contributions to $b \to s\nu\bar{\nu}$ and $b \to s\tau\tau$. Problem: Too large $B \to K^{(*)}\nu\bar{\nu}$ solved with $C^{(1)}_{23} \simeq C^{(3)}_{23}$.

Prediction for $b \to s\tau^+\tau^-$ as a function of $R(X)/R(X)_{SM}$

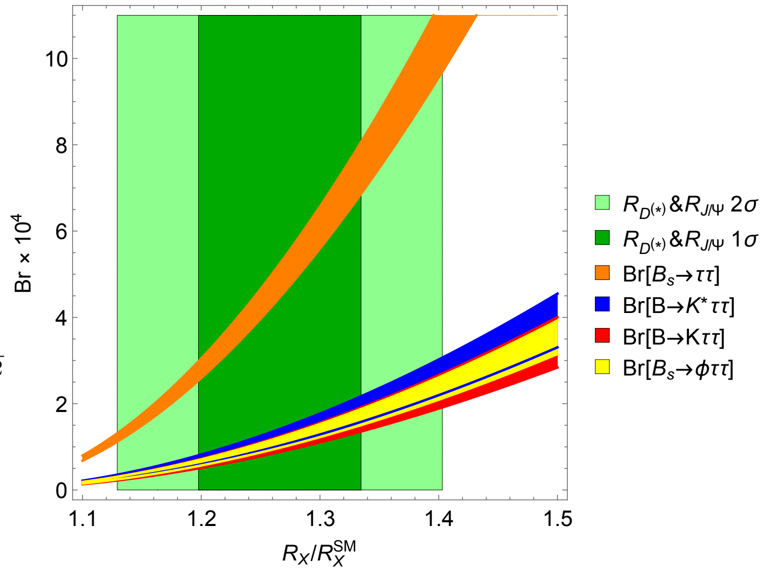
Consequence $b \to c\tau^-\nu_\tau$ and $b \to s\tau^+\tau^-$ generated together....

$$C_{9(10)\tau} \simeq C_{9,10}^{SM} - (+)\Delta$$

$$\Delta = 2\frac{\pi}{\alpha_{em}}\frac{V_{cb}}{V_{ts}^*}\left(\sqrt{\frac{R(X)}{R(X)_{SM}}} - 1\right) \simeq \mathcal{O}(100)$$

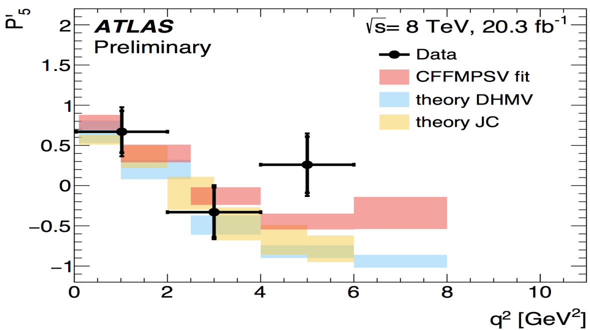
$$\mathrm{BR}(B_s \to \tau\tau) \quad = \mathrm{BR}(B_s \to \tau\tau)_{SM} \times \frac{\Delta^2}{C_{10}^{\mathrm{SM}\,2}}$$

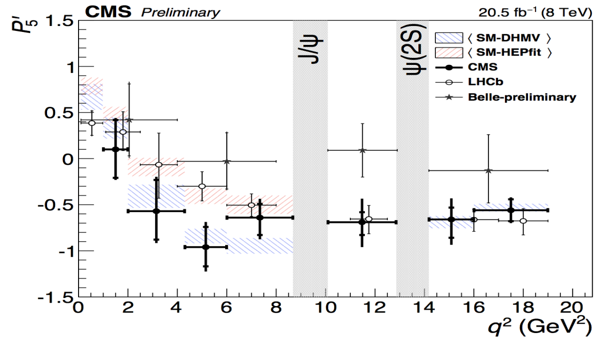
$$\mathrm{BR}(B \to K\tau\tau)_{fullq^2} = (8.8 \pm 0.8) \times 10^{-9}\Delta^2$$
$$\mathrm{BR}(B \to K^*\tau\tau)_{fullq^2} = (10.1 \pm 0.8) \times 10^{-9}\Delta^2$$
$$\mathrm{BR}(B_s \to \phi\tau\tau)_{fullq^2} = (9.1 \pm 0.5) \times 10^{-9}\Delta^2$$



ATLAS and CMS also!

⇒ ATLAS & CMS proven able to measure optimized observables. **Method**: folding technique.
Plots include two theory predictions and a fit CFFMPSV (not a prediction) to LHCb:





- The full basis (except P_2) is measured P_1, P_4', P_5', P_6', P_8' and F_L (large-recoil).
- ATLAS observe a large deviation in P_5' in agreement with LHCb and Belle.
- Also a large deviation in P_4' is observed in disagreement with LHCb and Belle.
- Only P_1 and P_5', P_5' seems consistent with SM (except [6-8]). CMS in tension with LHCb, Belle, ATLAS.
- Suggestions to test the robustness of analysis:
  - extract F_L , P_1 and P_5' from same folding like ATLAS and LHCb. Important to test correct normalization.
  - Implement directly the constraint: $P_5'^2 - 1 \leq P_1$

Few misconceptions on a global analysis

"It is not possible to get a large significance from a set of 2-3 sigma tensions".

This misleading statement confuses and mixes:
the pulls of data versus SM predictions WITH the Pull$_{\rm SM}$ that TEST an hyp. of NP versus SM hyp.

- *A global fit can help to distinguish a set of statistical fluctuations from a* **coherent** *set of deviations consistent with a NP hypothesis. Example:*

  $\rightarrow$ A set of 2-3 σ pulls taken together gives a 5.7σ of Pull$_{\rm SM}$ for a solution with $C_9^{\rm NP} = -1.1$.
  $\rightarrow$ SAME set of 2-3 σ but only changing the SIGN of a few of them the significance of Pull$_{\rm SM}$ drops to 0.7 σ.

- *A* **large deviation** *in one single observable (or a few) may be* **not significant**. *One out of 175 observables having a tension of 5 σ w.r.t the SM is not very significant ("Look-elsewhere effect"). The global fit accounts for this automatically and the Pull$_{SM}$ could be in the range 1-2σ.*

- **Theory+experimental correlations are fundamental.** Example: the fit with no correlations gives a Pull$_{SM} > 8\sigma$ for many NP hypothesis.

Different Form Factor determinations

B-meson distribution amplitudes.

FF-KMPW	$F^i_{BK^{(*)}}(0)$	b^i_1
f^+_{BK}	$0.34^{+0.05}_{-0.02}$	$-2.1^{+0.9}_{-1.6}$
f^0_{BK}	$0.34^{+0.05}_{-0.02}$	$-4.3^{+0.8}_{-0.9}$
f^T_{BK}	$0.39^{+0.05}_{-0.03}$	$-2.2^{+1.0}_{-2.00}$
V^{BK^*}	$\mathbf{0.36^{+0.23}_{-0.12}}$	$-4.8^{+0.8}_{-0.4}$
$A_1^{BK^*}$	$\mathbf{0.25^{+0.16}_{-0.10}}$	$0.34^{+0.86}_{-0.80}$
$A_2^{BK^*}$	$0.23^{+0.19}_{-0.10}$	$-0.85^{+2.88}_{-1.35}$
$A_0^{BK^*}$	$0.29^{+0.10}_{-0.07}$	$-18.2^{+1.3}_{-3.0}$
$T_1^{BK^*}$	$0.31^{+0.18}_{-0.10}$	$-4.6^{+0.81}_{-0.41}$
$T_2^{BK^*}$	$0.31^{+0.18}_{-0.10}$	$-3.2^{+2.1}_{-2.2}$
$T_3^{BK^*}$	$0.22^{+0.17}_{-0.10}$	$-10.3^{+2.5}_{-3.1}$

Table: The $B \to K^{(*)}$ form factors from LCSR and their z-parameterization.

Light-meson distribution amplitudes+EOM (NOT LATEST).

- Interestingly in BSZ (update from BZ) most relevant FF from BZ moved towards KMPW. For example:

$$V^{BZ}(0) = 0.41 \to 0.37 \quad T_1^{BZ}(0) = 0.33 \to 0.31$$

- The size of uncertainty in BSZ = size of error of p.c.

FF-BSZ	$B \to K^*$	$B_s \to \phi$	$B_s \to K^*$
$A_0(0)$	0.391 ± 0.035	0.433 ± 0.035	0.336 ± 0.032
$A_1(0)$	$\mathbf{0.289 \pm 0.027}$	0.315 ± 0.027	0.246 ± 0.023
$A_{12}(0)$	0.281 ± 0.025	0.274 ± 0.022	0.246 ± 0.023
$V(0)$	$\mathbf{0.366 \pm 0.035}$	0.407 ± 0.033	0.311 ± 0.030
$T_1(0)$	0.308 ± 0.031	0.331 ± 0.030	0.254 ± 0.027
$T_2(0)$	0.308 ± 0.031	0.331 ± 0.030	0.254 ± 0.027
$T_{23}(0)$	0.793 ± 0.064	0.763 ± 0.061	0.643 ± 0.058

Table: Values of the form factors at $q^2 = 0$ and their uncertainties.