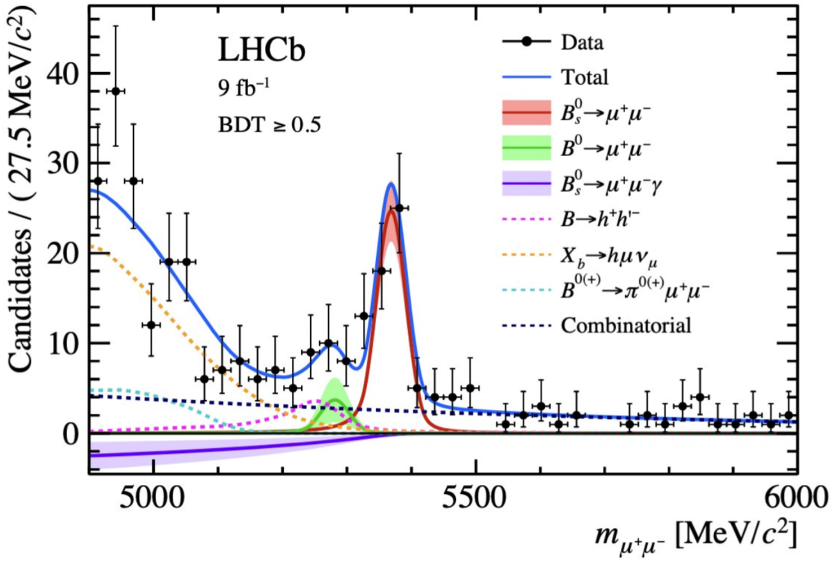
The relevance of Bs → ɣ FFs within and beyond the Standard Model

Work in collaboration with Diego Guadagnoli, Camille Normand and Silvano Simula

[based on JHEP ’23 (2303.02174) and JHEP ‘23 (2308.00034)]

Ludovico Vittorio (LAPTh & CNRS, Annecy, France)

Workshop on radiative leptonic B decays, Marseille – 29th February 2024



(from LHCb-PAPER-2021-007)

Radiative-and-leptonic Bs decays

A novel possibility to analyze $b \to s$ quark transitions is the study of rare radiative-and-leptonic Bs decays. This is experimentally challenging, and yet LHCb has recently set a limit (very close to the SM signal):

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}} = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} < 2.0 \times 10^{-9}$$

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Several advantages from the phenomenological point of view:

1. **No chirality suppression** (thanks to the additional photon): **enhancement w.r.t. the leptonic counterpart**!
2. **Sensitivity to a larger set of WCs**: not only O_{10}(‘), also O_7(‘) and O_9(‘) (*reminder:* O_9(‘) *and* O_{10}(‘) *are particularly relevant @ high-q2*)
3. **Two ways to detect it experimentally:**

- ***directly* (*i.e*. w/ photon reconstruction)**
- ***indirectly* (*i.e*. w/out photon reconstruction)** **[Dettori et al, PLB ’17 (1610.00629)]**

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See talks by Irene Bachiller and Camille Normand

Radiative-and-leptonic decays in Effective Field Theory

Standard WET approach:

$$\mathcal{H} = -\frac{4G_F}{\sqrt{2}}\lambda_{\rm CKM}\left[\frac{\alpha_{em}}{4\pi}\left(\sum_i C_i \mathcal{O}_i + \sum_i C_i' \mathcal{O}_i'\right)\right]$$

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Melikhov and Nikitin, Phys. Rev. D 70 (2004) 114028
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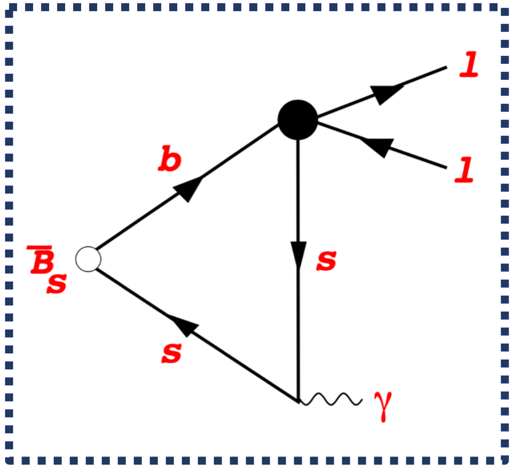

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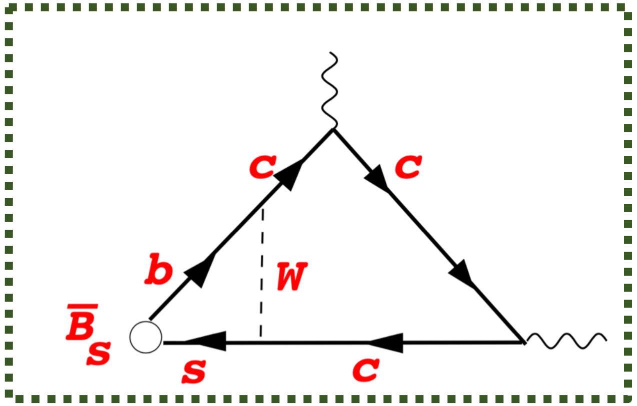

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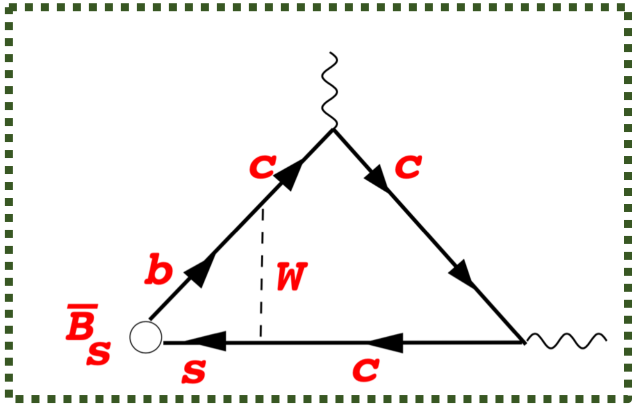
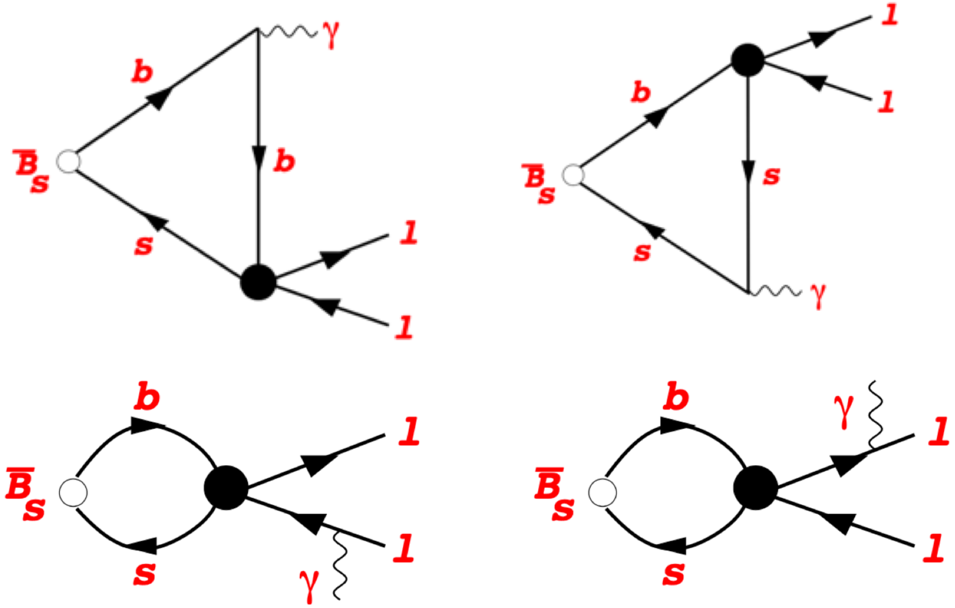


Important issue: **<u>only 4 diagrams</u> give the most important contribution at high-q2, *i.e.***



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→ **Main idea:** *HQET scaling of FFs parameters from the Ds-sector to the Bs-sector, starting from Lattice QCD (LQCD) data available for the Ds-sector @ high-q2*

Methodological overview of the GNSV approach to hadronic FFs

Each FF obeys a dispersion relation of this form:

$$V^{D_s}_{\perp[\parallel]}(q^2) = \frac{1}{\pi}\int_0^\infty dt \frac{\mathrm{Im}[V^{D_s}_{\perp[\parallel]}(t)]}{t-q^2} = \frac{r^{D_s^*[D_{s1}]}_{\perp[\parallel]}}{1-q^2/m^2_{D_s^*[D_{s1}]}} + \ldots$$

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Opportunity to test different pole structures ($\chi = \perp, \|$): for instance

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***General methodology*: the free parameters of each ansaetze can be determined through fits to lattice data !**

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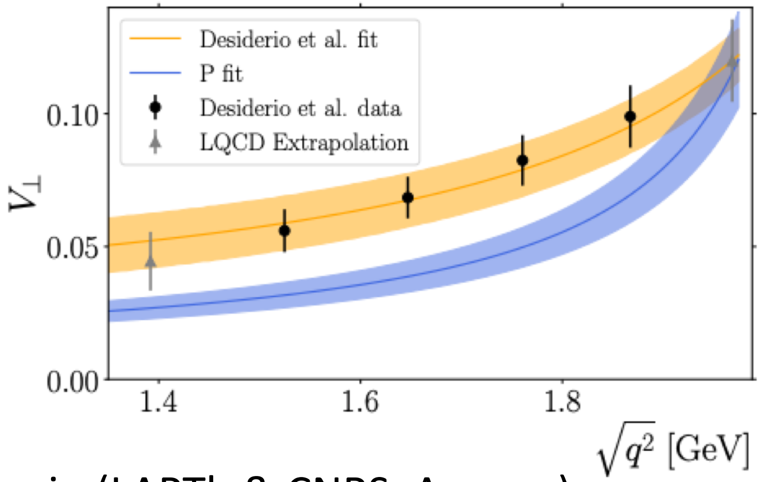

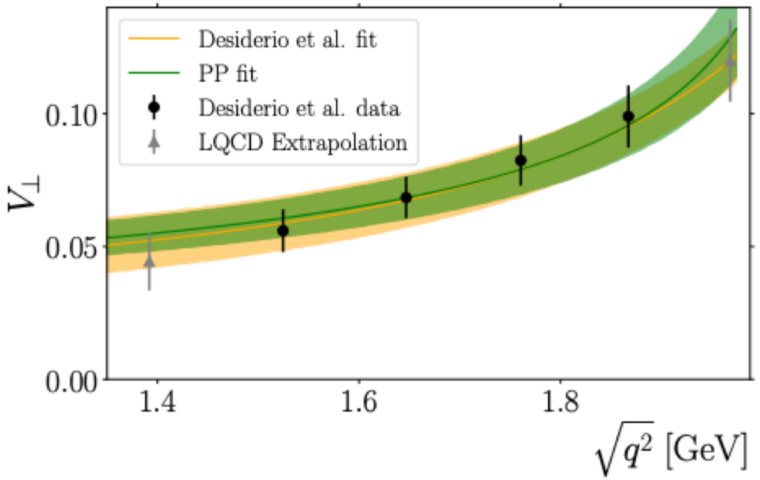

LQCD data from Desiderio et al., PRD '21 (2006.05358)

P fit $\quad r_{\perp}^{D_s^*} = 0.015(2), \qquad \chi^2 = 32$

PP fit $\quad r_{\perp 1} = 0.009 \pm 0.003, \quad r_{\perp 2} = 0.029 \pm 0.005 \qquad \chi^2 = 1.5$

Methodological overview of the GNSV approach to hadronic FFs

Once inferred the residues in the Ds sector, the extrapolation to the Bs-sector is based on the 3-couplings:

$$g_{D_s^* D_s \gamma} = Q_s \mu_s^{\perp 1} + Q_c \mu_c^{\perp 1} \,, \quad g_{D_{s1} D_s \gamma} = -Q_s \mu_s^{\parallel} + Q_c \mu_c^{\parallel} \,,$$
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Quark magnetic moments		$B_s \to \gamma$ FFs parameters	
$\mu_s^{\perp 1}$	$-0.22(8)$	$r_{\perp 1}^{B_s}$	0.017 ± 0.006
$\mu_b^{\perp 1}$	$-0.019(6)$	$r_{\perp 2}^{B_s}$	0.088 ± 0.030
$\mu_s^{\perp 2}$	$-2.6(8)$	$r_{\parallel}^{B_s}$	-0.043 ± 0.004
$\mu_b^{\perp 2}$	$-0.22(6)$	$\rho(r_{\perp 1}, r_{\perp 2})$	-0.21
$\mu_s^{\parallel}$	$-0.46(4)$		
$\mu_b^{\parallel}$	$-0.038(3)$		

Starting from LQCD data in Desiderio et al., PRD ’21 (2006.05358)

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Final ingredient for the computation of BR(Bs → *μμγ*) @ high-q2: *charmonia* !

All broad-charmonium states are included as properly normalized Breit-Wigner (BW) poles, that shift the Wilson coefficient C_9 in this way:

$$C_9 \to C_9 - \frac{9\pi}{\alpha^2}\bar{C}\sum_V |\eta_V| e^{i\delta_V} \frac{\hat{m}_V\,\mathcal{B}(V\to\mu^+\mu^-)\,\hat{\Gamma}^V_{\rm tot}}{\hat{q}^2 - \hat{m}_V^2 + i\hat{m}_V\hat{\Gamma}^V_{\rm tot}}$$

Kruger and Sehgal, PLB ‘96 (hep-ph/9603237)

$$\bar{C} = C_1 + C_2/3 + C_3 + C_4/3 + C_5 + C_6/3$$

Values taken from
Beneke, Bobeth and Wang, JHEP ‘20 [2008.12494]

$m_{\psi(2S)}$	3.686 GeV	PDG ‘22	$\Gamma_{\psi(2S)}$	0.294×10^{-3} GeV	PDG ‘22
$m_{\psi(3770)}$	3.774 GeV		$\Gamma_{\psi(3770)}$	27.2×10^{-3} GeV	
$m_{\psi(4040)}$	4.039 GeV		$\Gamma_{\psi(4040)}$	80×10^{-3} GeV	
$m_{\psi(4160)}$	4.191 GeV		$\Gamma_{\psi(4160)}$	70×10^{-3} GeV	
$m_{\psi(4415)}$	4.421 GeV		$\Gamma_{\psi(4415)}$	62×10^{-3} GeV	
$\mathcal{B}(\psi(2S)\to\ell\ell)$	8.0×10^{-3}	PDG ‘22	$\delta_{\psi(2S)}$	0	BES Coll.
$\mathcal{B}(\psi(3770)\to\ell\ell)$	9.6×10^{-6}		$\delta_{\psi(3770)}$	0	
$\mathcal{B}(\psi(4040)\to\ell\ell)$	10.7×10^{-6}		$\delta_{\psi(4040)}$	$133\times\pi/180$	
$\mathcal{B}(\psi(4160)\to\ell\ell)$	6.9×10^{-6}		$\delta_{\psi(4160)}$	$301\times\pi/180$	
$\mathcal{B}(\psi(4415)\to\ell\ell)$	2.0×10^{-5}		$\delta_{\psi(4415)}$	$246\times\pi/180$	

arXiv:0705.4500

The full formula for BR(Bs → $\mu\mu\gamma$)

$$\frac{d^2\Gamma^{(1)}}{d\hat{s}\,d\hat{t}} = \frac{G_F^2\,\alpha_{em}^3\,M_1^5}{2^{10}\,\pi^4}\,\left|V_{tb}\,V_{tq}^*\right|^2 \left[x^2\,B_0\left(\hat{s},\,\hat{t}\right) + x\,\xi\left(\hat{s},\hat{t}\right)\,\tilde{B}_1\left(\hat{s},\,\hat{t}\right) + \xi^2\left(\hat{s},\hat{t}\right)\,\tilde{B}_2\left(\hat{s},\,\hat{t}\right)\right], \tag{6.1}$$

$$B_0\left(\hat{s},\,\hat{t}\right) = \left(\hat{s} + 4\hat{m}_l^2\right)\left(F_1\left(\hat{s}\right) + F_2\left(\hat{s}\right)\right) - 8\hat{m}_l^2\,\left|C_{10A}(\mu)\right|^2\left(F_V^2\left(q^2\right) + F_A^2\left(q^2\right)\right),$$

$$\tilde{B}_1\left(\hat{s},\,\hat{t}\right) = 8\,\Big[\hat{s}\,F_V(q^2)\,F_A(q^2)\,Re\left(C_{9V}^{eff\,*}(\mu,q^2)\,C_{10A}(\mu)\right)$$

$$+\,\hat{m}_b\,F_V(q^2)\,Re\left(C_{7\gamma}^*(\mu)\,\bar{F}_{TA}^*(q^2)\,C_{10A}(\mu)\right) + \hat{m}_b\,F_A(q^2)\,Re\left(C_{7\gamma}^*(\mu)\,\bar{F}_{TV}^*(q^2)\,C_{10A}(\mu)\right)\Big],$$

$$\tilde{B}_2\left(\hat{s},\,\hat{t}\right) = \hat{s}\,\left(F_1\left(\hat{s}\right) + F_2\left(\hat{s}\right)\right),$$

$$F_1\left(\hat{s}\right) = \left(\left|C_{9V}^{\rm eff}(\mu,q^2)\right|^2 + \left|C_{10A}(\mu)\right|^2\right)F_V^2(q^2) + \left(\frac{2\hat{m}_b}{\hat{s}}\right)^2\left|C_{7\gamma}(\mu)\,\bar{F}_{TV}(q^2)\right|^2$$

$$+\,\frac{4\hat{m}_b}{\hat{s}}\,F_V(q^2)\,Re\left(C_{7\gamma}(\mu)\,\bar{F}_{TV}(q^2)\,C_{9V}^{eff\,*}(\mu,q^2)\right),$$

$$F_2\left(\hat{s}\right) = \left(\left|C_{9V}^{\rm eff}(q^2,\mu)\right|^2 + \left|C_{10A}(\mu)\right|^2\right)F_A^2(q^2) + \left(\frac{2\hat{m}_b}{\hat{s}}\right)^2\left|C_{7\gamma}(\mu)\,\bar{F}_{TA}(q^2)\right|^2$$

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Emission of the photon from valence quarks or FCNC vertex *(DE component)*

$$\frac{d^2\Gamma^{(2)}}{d\hat{s}\,d\hat{t}} = \frac{G_F^2\,\alpha_{em}^3\,M_1^5}{2^{10}\,\pi^4}\,\left|V_{tb}\,V_{tq}^*\right|^2\left(\frac{8\,f_{B_q}}{M_B}\right)^2\,\hat{m}_l^2\,\left|C_{10A}(\mu)\right|^2\left[\frac{\hat{s} + x^2/2}{(\hat{u} - \hat{m}_l^2)(\hat{t} - \hat{m}_l^2)} - \left(\frac{x\,\hat{m}_l}{(\hat{u} - \hat{m}_l^2)\,(\hat{t} - \hat{m}_l^2)}\right)^2\right] \tag{6.2}$$

Bremsstrahlung

$$\frac{d^2\Gamma^{(12)}}{d\hat{s}\,d\hat{t}} = -\frac{G_F^2\,\alpha_{em}^3\,M_1^5}{2^{10}\,\pi^4}\,\left|V_{tb}\,V_{tq}^*\right|^2\,\frac{16\,f_{B_q}}{M_B}\,\hat{m}_l^2\,\frac{x^2}{(\hat{u} - \hat{m}_l^2)(\hat{t} - \hat{m}_{l34}^2)} \tag{6.3}$$

$$\times\left[\frac{2\,x\,\hat{m}_b}{\hat{s}}\,Re\left(C_{10A}^*(\mu)C_{7\gamma}(\mu)\bar{F}_{TV}(q^2,0)\right) + x\,F_V(q^2)\,Re\left(C_{10A}^*(\mu)C_{9V}^{\rm eff}(\mu,q^2)\right) + \xi(\hat{s},\hat{t})\,F_A(q^2)\,\left|C_{10A}(\mu)\right|^2\right].$$

Interference

Melikhov and Nikitin, Phys. Rev. D 70 (2004) 114028
Kozachuk, Melikhov and Nikitin, Phys. Rev. D 97 (2018) 053007
Guadagnoli, Melikhov and Reboud, Phys.Lett.B 760 (2016) 442-447 [fixes a typo in the interference term Γ12]

Impact of charmonium resonances on BR prediction

By focusing on the DE-only component of BR(Bs → $\mu\mu\gamma$) @ high-q2,
we find the following values for the BR:
(REMARK: DDILST computation gives results very similar to JPZ ones!)

$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)[4.2\ \text{GeV}, m_{B_s^0}]$	
GNSV	$(1.63 \pm 0.80) \times 10^{-10}$
KMN [6]	$(1.83 \pm 0.69) \times 10^{-10}$
JPZ [7]	$(1.90 \pm 0.53) \times 10^{-9}$
Influence of the choice of $T_{\perp,\parallel}$ (with $V_{\perp,\parallel}$ from this work)	
$T_{\perp,\parallel}$ from KMN	$(1.22 \pm 0.70) \times 10^{-10}$
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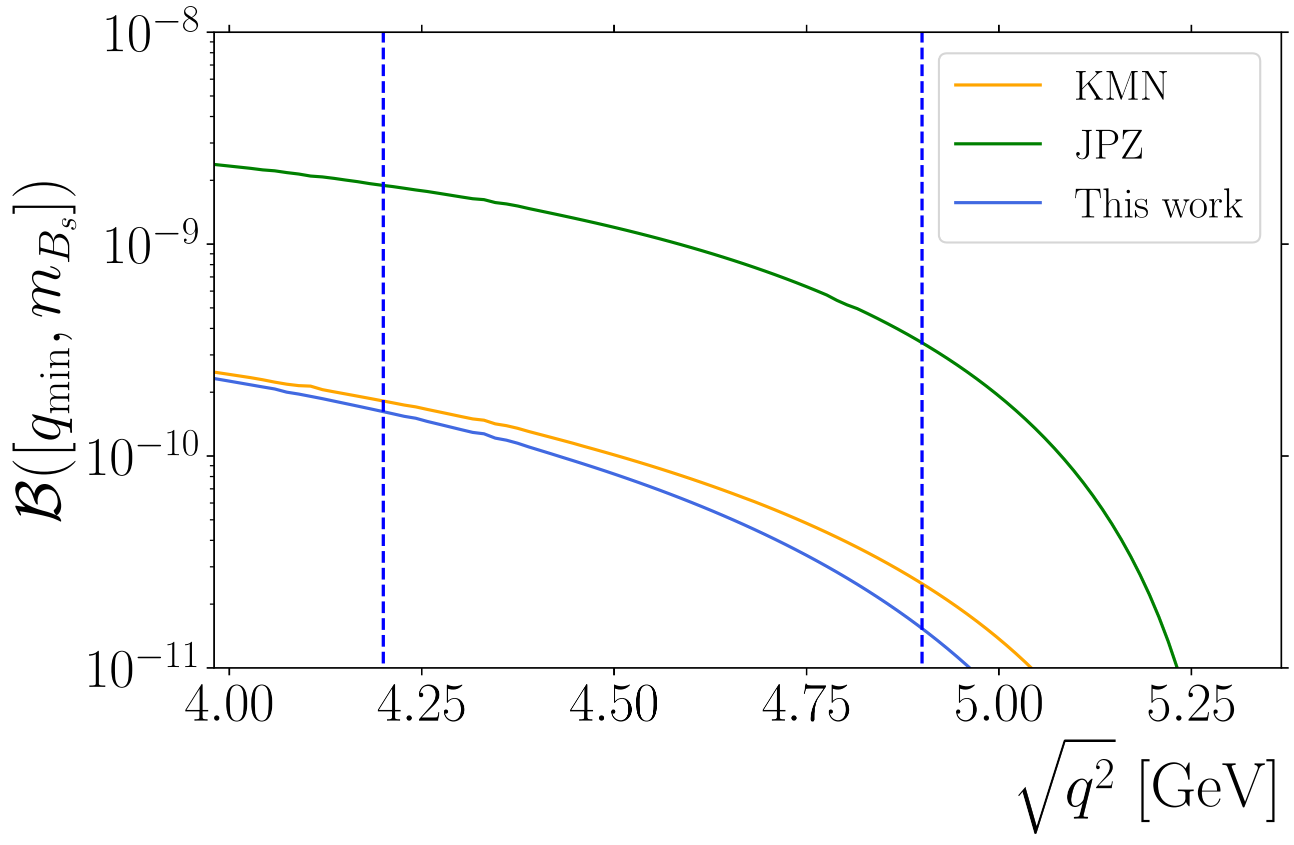

Guadagnoli, Normand, Simula, LV, JHEP '23 (2303.02174)

Impact of charmonium resonances on BR prediction

Negligible impact of tensor FFs …

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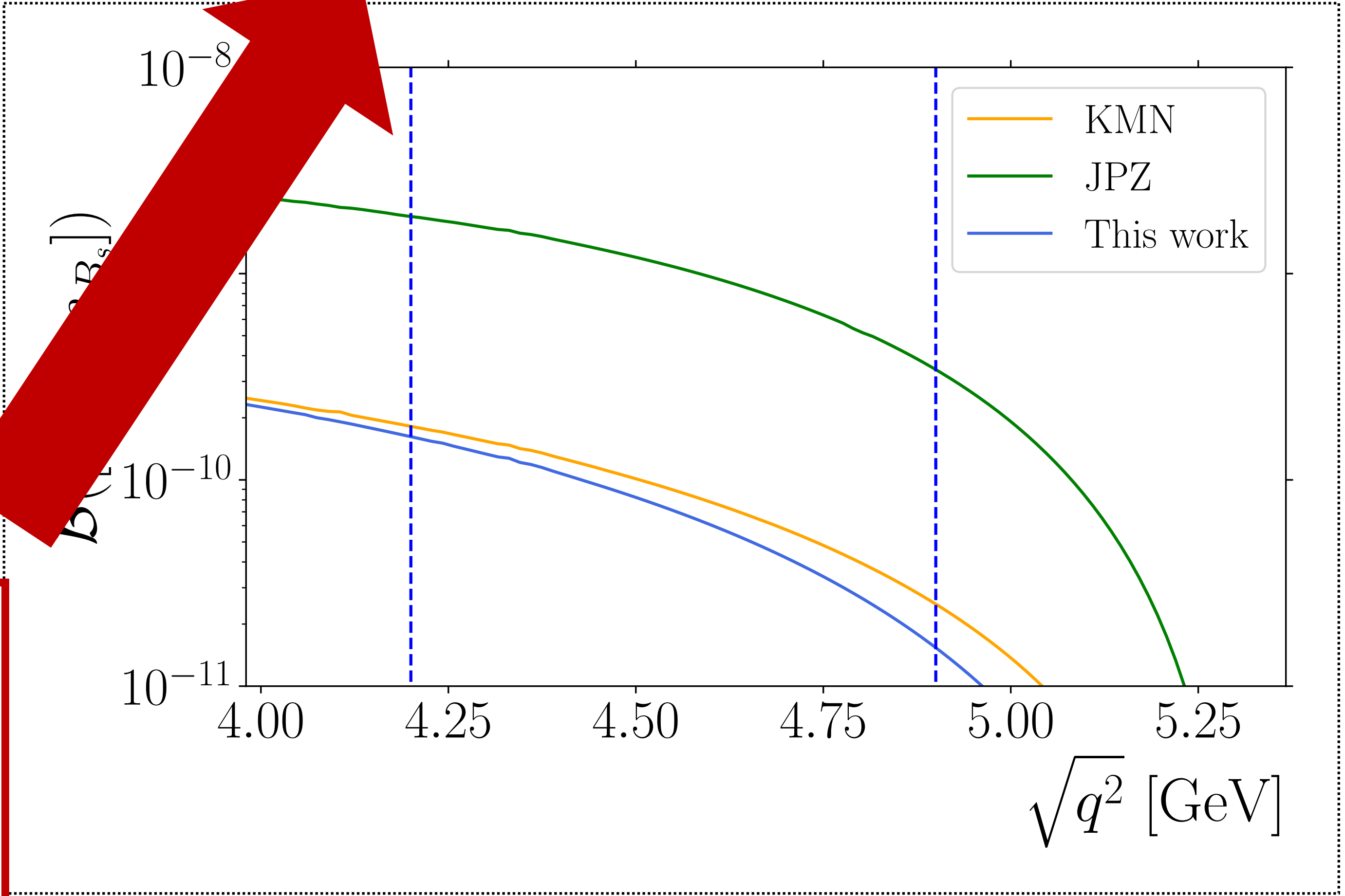

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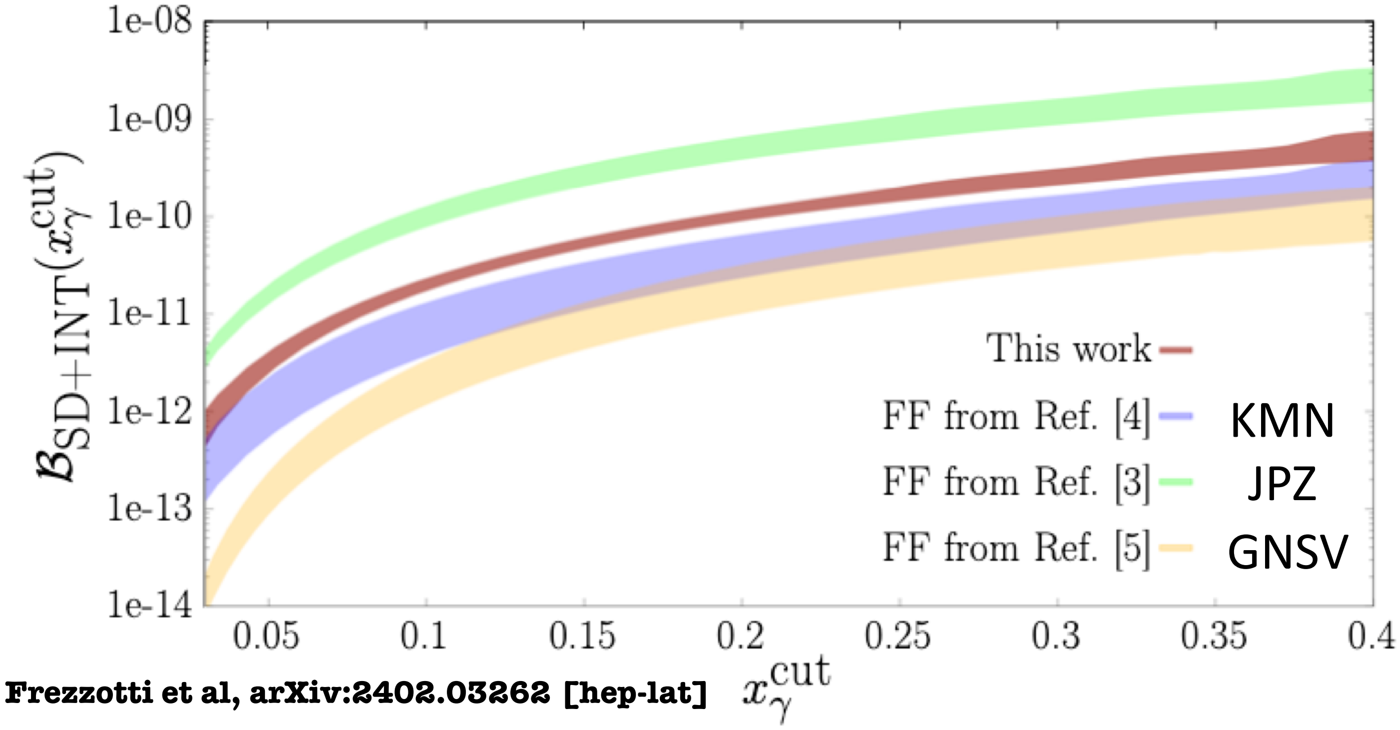

Frezzotti et al, arXiv:2402.03262 [hep-lat]

ETMC number (see Table VI): BR × 10^{10} = $5.3(1.7)$

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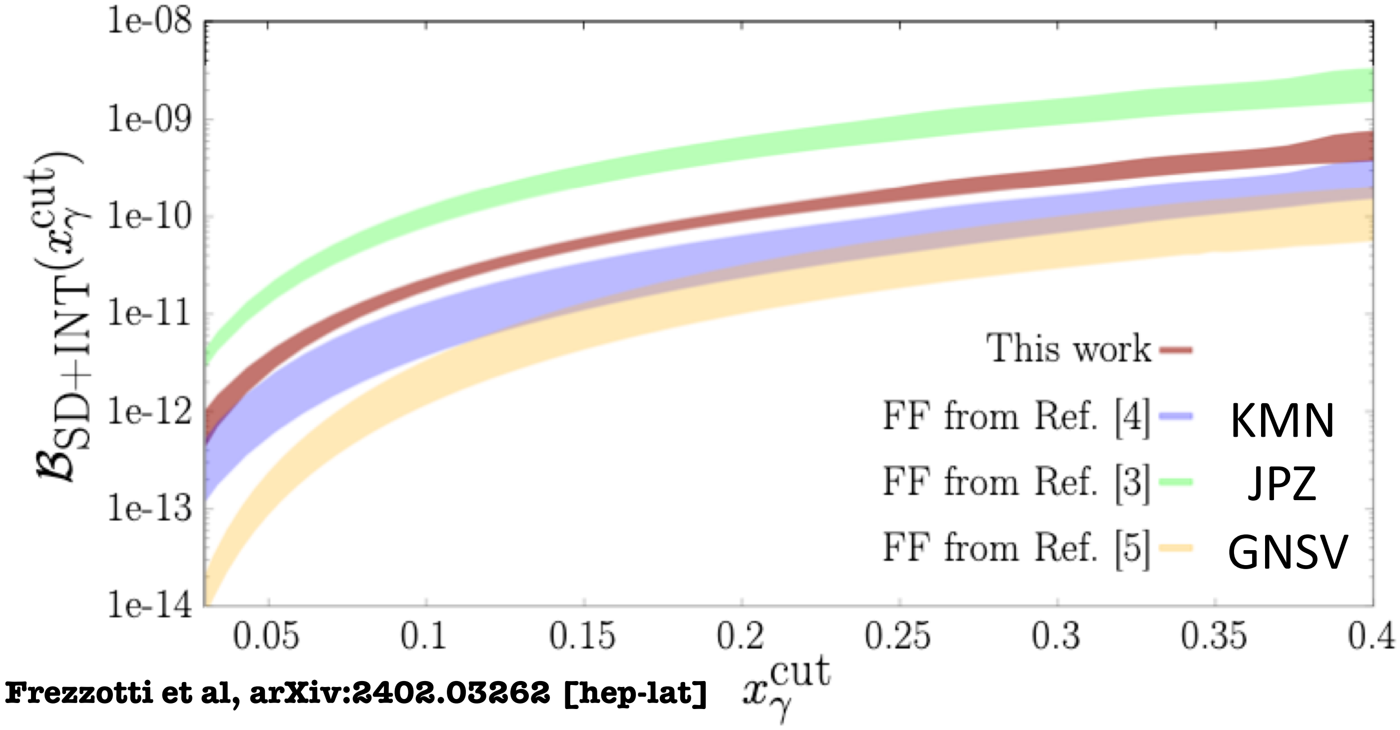

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Differences @ the 1.9σ – 2.2σ level despite the differences in the FFs values

Fundamental topic of discussion: treatment of broad-charmonium parameters!

Brief recap of the GNSV procedure within the SM

The procedure presented in **Guadagnoli, Normand, Simula, LV, JHEP '23 (2303.02174)** is based on a HQET scaling of FFs parameters from the Ds-sector to the Bs-sector, starting from LQCD data available for the Ds-sector @ high-q2.

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And what about Bs → ɣ beyond the Standard model ??

The relevance of $B_s \to \gamma$ beyond the SM

The $B_s \to \mu\mu\gamma$ channel can be used to study hypothetical New Physics (NP) effects affecting *b → s quark transition*. In fact, despite the disappearance of the R(K(*)) anomalies, we have several discrepancies among theory and experiments in semileptonic neutral-current *B* decays:

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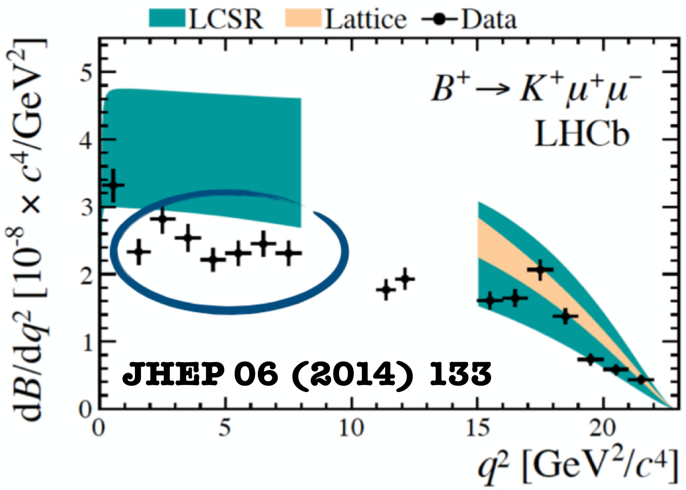

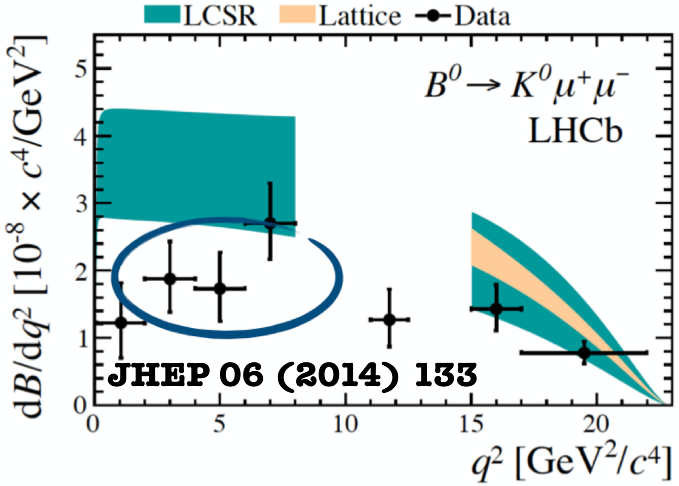

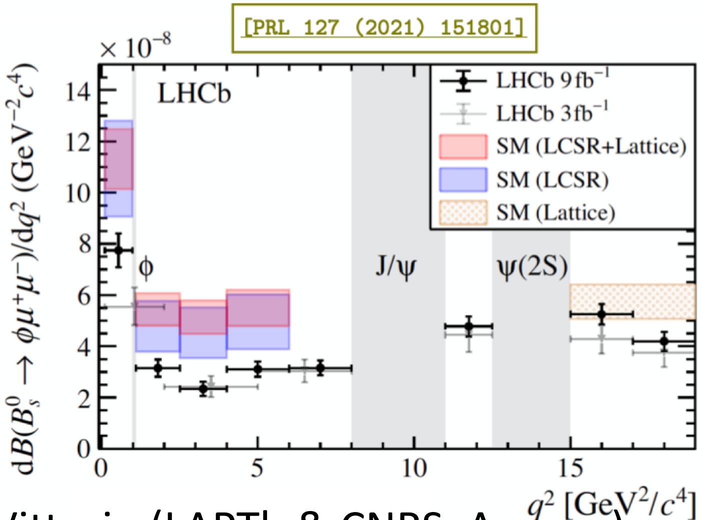

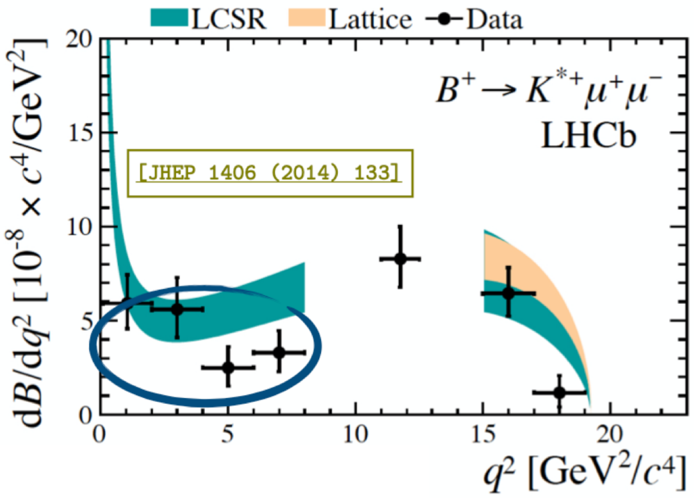

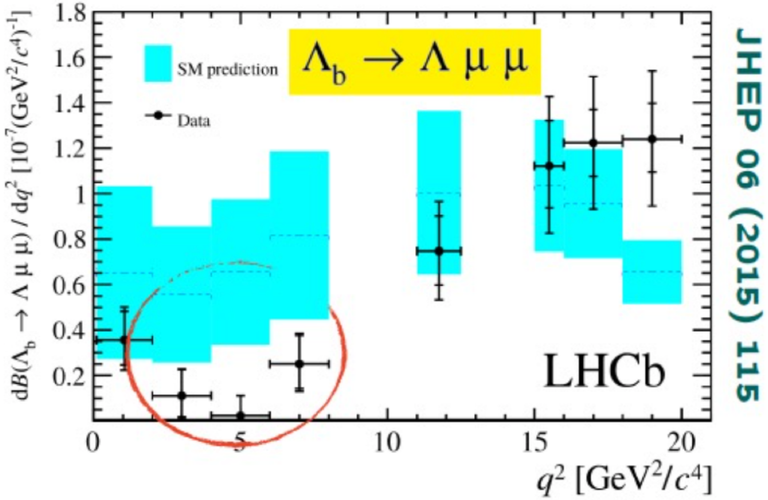

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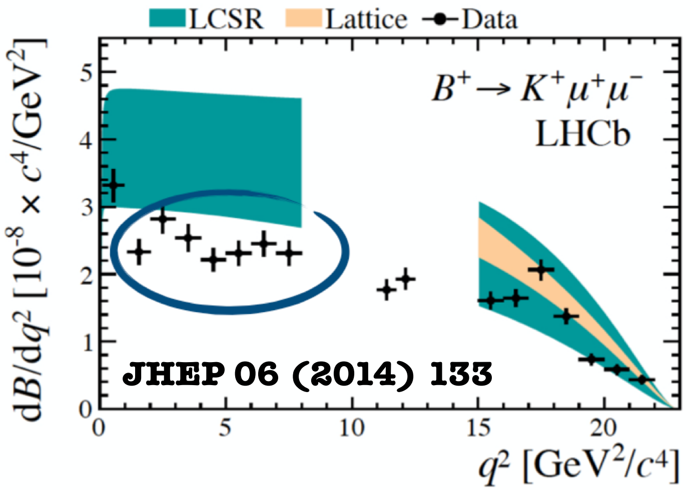
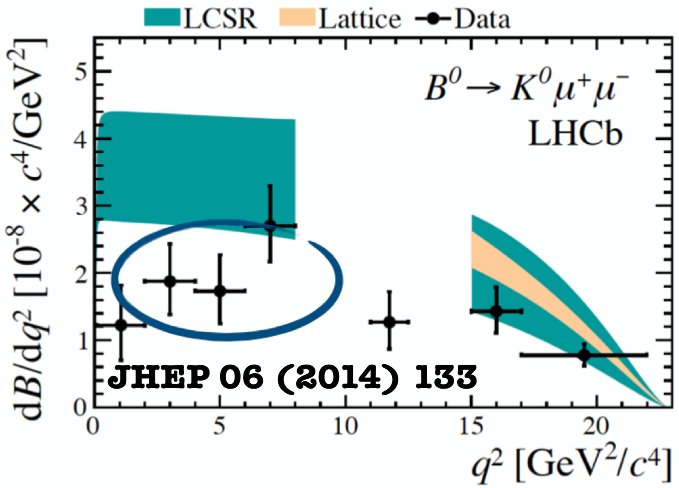
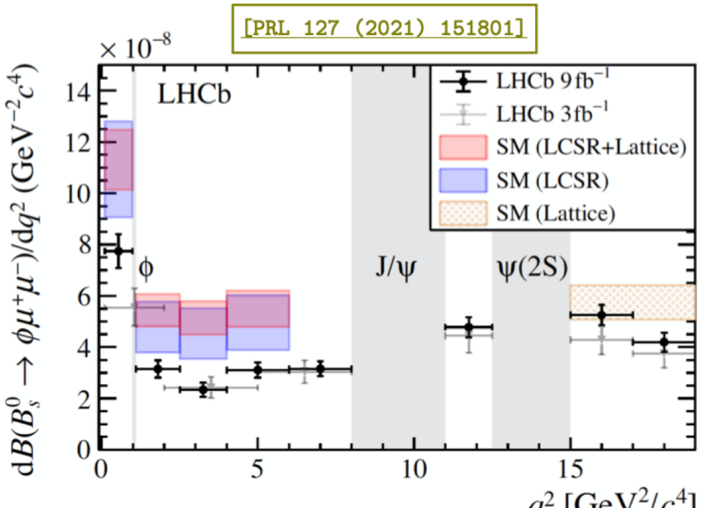
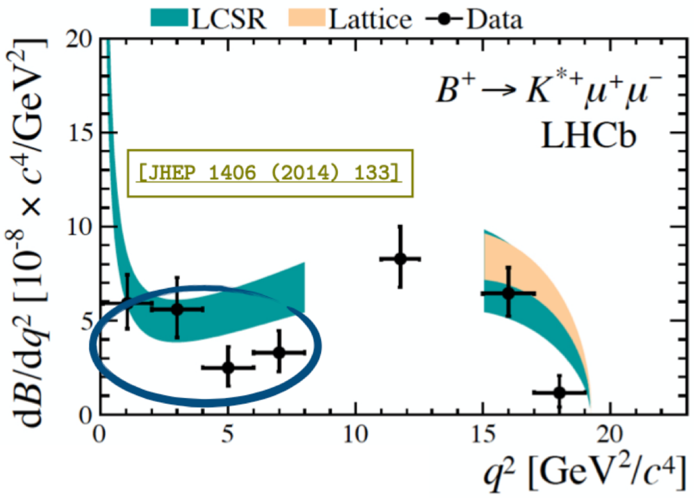
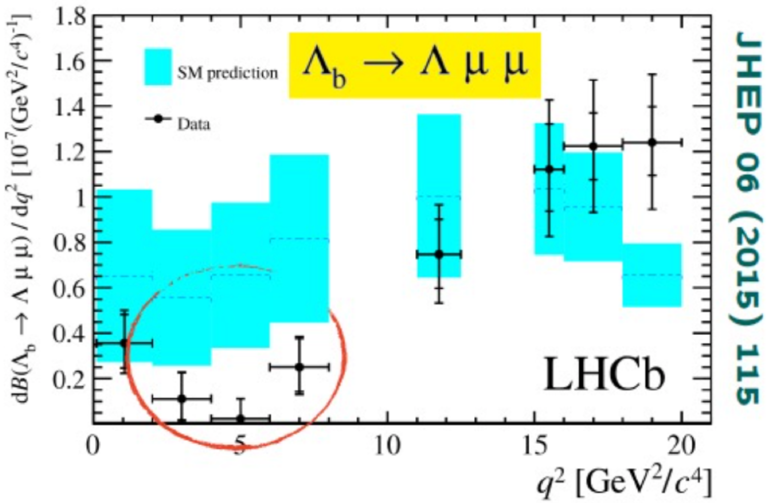




SM expectations seem to be *always above* experimental data …

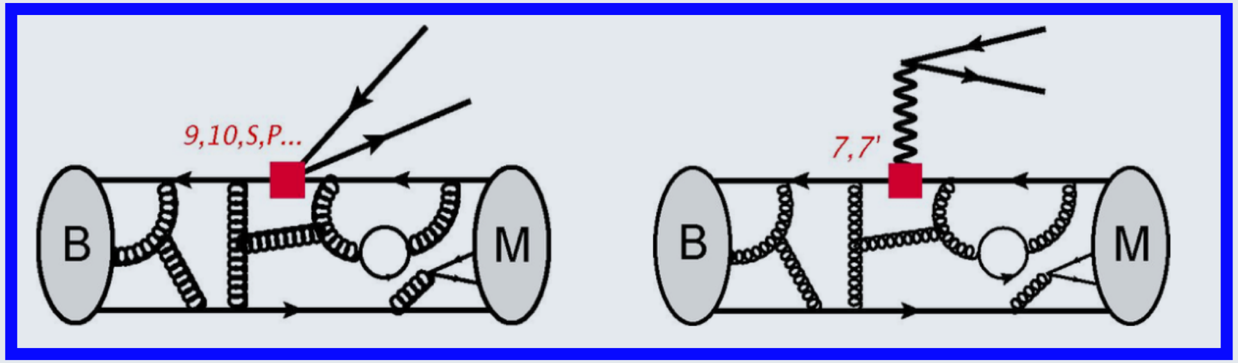


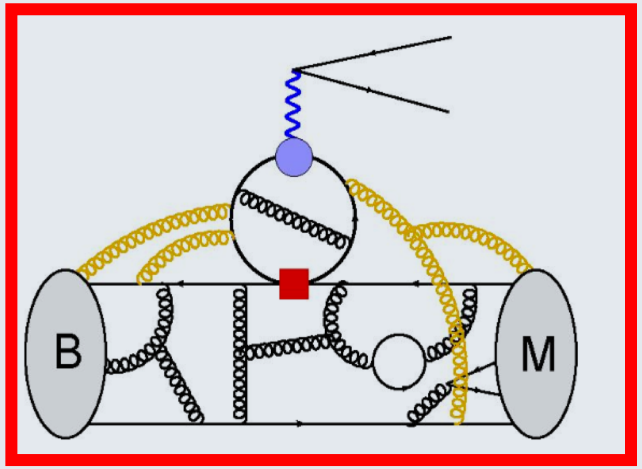




Semileptonic B decays theory in a nutshell

$$\mathcal{H}(b \to s\ell\ell) = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=1}^{10} C_i(\mu)\mathcal{O}_i(\mu)$$





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

$$\mathcal{H}_\mu(k,q) = i\int d^4x\, e^{iq\cdot x}\langle \bar{M}(k)|T\{\mathcal{J}_\mu^{\text{em}}(x), \mathcal{C}_i\mathcal{O}_i\}|\bar{B}(q+k)\rangle$$

Non-local form-factors

M. Reboud's talk @ LHC Impilication Workshop 2022 @ CERN

$$\mathcal{F}_\mu(k,q) = \langle \bar{M}(k)|\bar{s}\gamma_\mu b_L|\bar{B}(q+k)\rangle$$

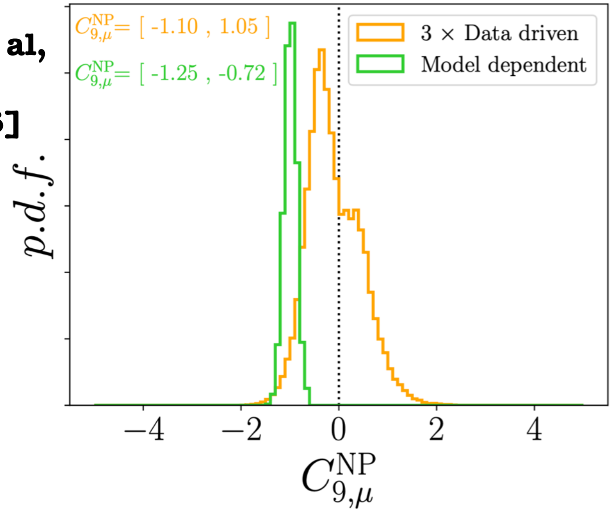
local form-factors

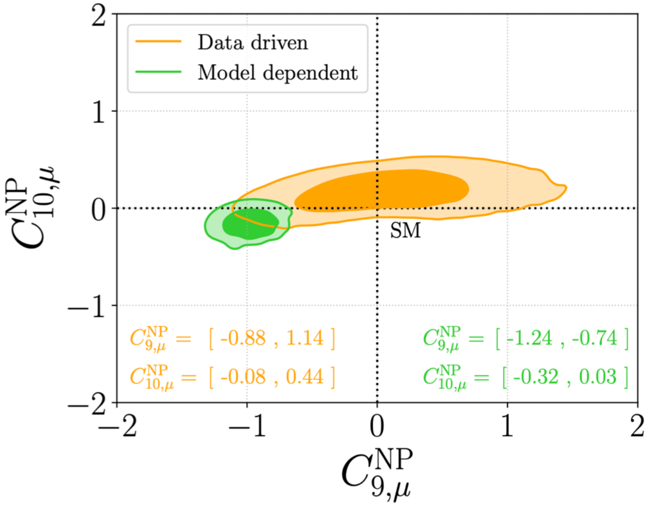
$$Q_2^c = (\bar{s}_L\gamma_\mu c_L)(\bar{c}_L\gamma^\mu b_L)$$

Important issue concerning non-local FFs

There is **not** general consensus on the magnitude of the contributions coming from these non-local FFs:

M. Ciuchini et al, PRD '23 [2212.10516]





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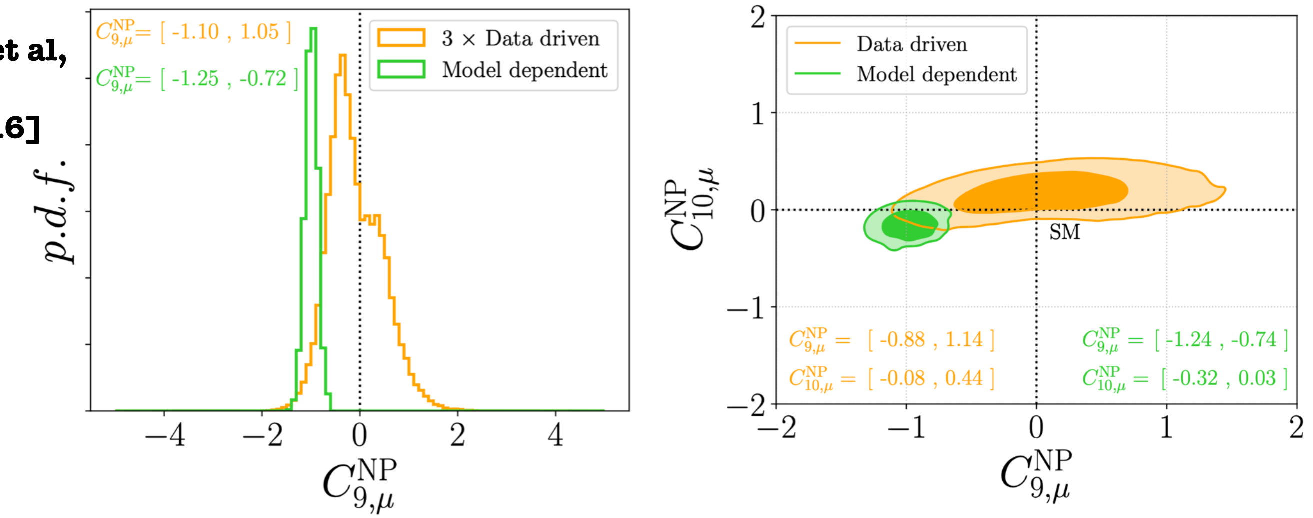

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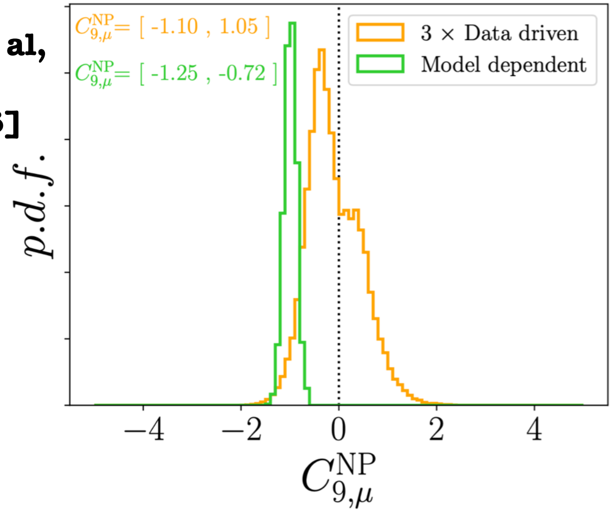

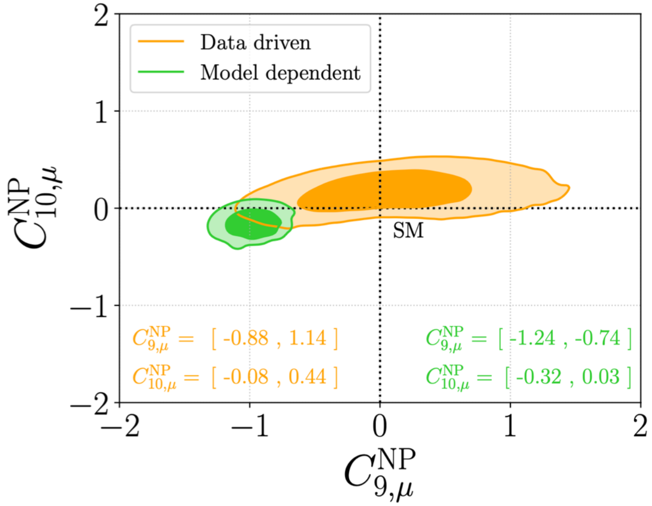

The «hypothetical» presence of NP seems to depend on the way in which the non-local FFs are described !

Data-driven: naïve q^2-expansion of the form

$$H_V^- \propto \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{SM}+h_-^{(0)}\right)\widetilde{T}_{L-} - 16\pi^2 h_-^{(2)}\, q^4\right] + \left(C_9^{SM}+h_-^{(1)}\right)\widetilde{V}_{L-}\,,$$

Clear advantage: it is transparent the interplay between hadronic and possible NP contributions!

M. Ciuchini et al, JHEP '16 [1512.07157], EPJC '17 [1704.05447], EPJC '19 [1903.09632], PRD '21 [2011.01212], EPJC '23 [2110.10126], PRD '23 [2212.10516]

Model-depedent: it assumes the *h*-terms on the left $[h_-^{(0)}, h_-^{(1)}, h_-^{(2)}]$ to be negligible.

Underlying idea: this assumption is supported at present by the **application of dispersion relations, analiticity and unitarity (together with LCSR data)** to the description of non-local FFs !

C. Bobeth et al, EPJC '18 [1707.07305]
M. Chrzaszcz et al, JHEP '19 [1805.06378]
N. Gubernari et al, JHEP '21 [2011.09813], JHEP '22 [2206.03797], 2305.06301

$B_s \to \mu\mu\gamma$ as a golden channel to study NP

KEY IDEA: **high-q2 observables are sensitive to the very same short-distance physics present in B \to K(*) decays, without being affected by the same long-distance effects !**

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$B_s \to \mu\mu\gamma$ as a perfect candidate: if there is really NP in B \to K(*) decays, *i.e.* if there is really a NP contribution to C_9, this effect must influence as well the BR($B_s \to \mu\mu\gamma$) @ high-q2

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However, we do not have a direct measurement of BR($B_s \to \mu\mu\gamma$) @ high-q2,
but only an experimental bound:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}} = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} < 2.0 \times 10^{-9}$$

LHCb Collaboration, LHCb-PAPER-2021-007 & LHCb-PAPER-2021-008

Thus, the best that we can do at this stage is a sensitivity study !

$B_s \to \mu\mu\gamma$ as a golden channel to study NP

Main ingredients of our sensitivity study:

1. ***Identification of NP benchmarks***
   from semileptonic neutral-current B decays:

	NP shift		ℓ-specific + ℓ-univ. parts
$(k = 9,\, 10)$	δC_k^{bsee}	$\equiv$	$\delta C_k^{(e)} + \delta C_k^{u(e,\mu)}$
	$\delta C_k^{bs\mu\mu}$	$\equiv$	$\delta C_k^{(\mu)} + \delta C_k^{u(e,\mu)}$

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$(k = 9,\ 10)$

$$\left[\ \delta C_9^{(\ell)} = -\delta C_{10}^{(\ell)} \equiv \delta C_{LL}^{(\ell)}/2\ \right]$$

by fitting the data (see back-up slides for their list)

Scenario	Best-fit point	1σ Interval	$\sqrt{\chi^{2,\text{SM}} - \chi^2}$
$(\delta C_9^{u(e,\mu)}, \delta C_{10}^{u(e,\mu)}) \in \mathbb{R}$	$(-0.88, +0.30)$	$([-1.08, -0.56], [0.15, 0.46])$	5.5
$\delta C_{LL}^{u(e,\mu)}/2 \in \mathbb{C}$	$-0.70 - 1.36i$	$[-1.00, -0.54] + i[-1.77, -0.54]$	5.8
$\delta C_9^{u(e,\mu)} \in \mathbb{C}$	$-1.08 + 0.10i$	$[-1.31, -0.85] + i[-0.70, +0.85]$	6.4
$\delta C_{10}^{u(e,\mu)} \in \mathbb{C}$	$+0.68 + 1.40i$	$[+0.38, +1.00] + i[+0.69, +1.92]$	3.2

Guadagnoli, Normand, Simula, LV, JHEP '23 [2308.00034]

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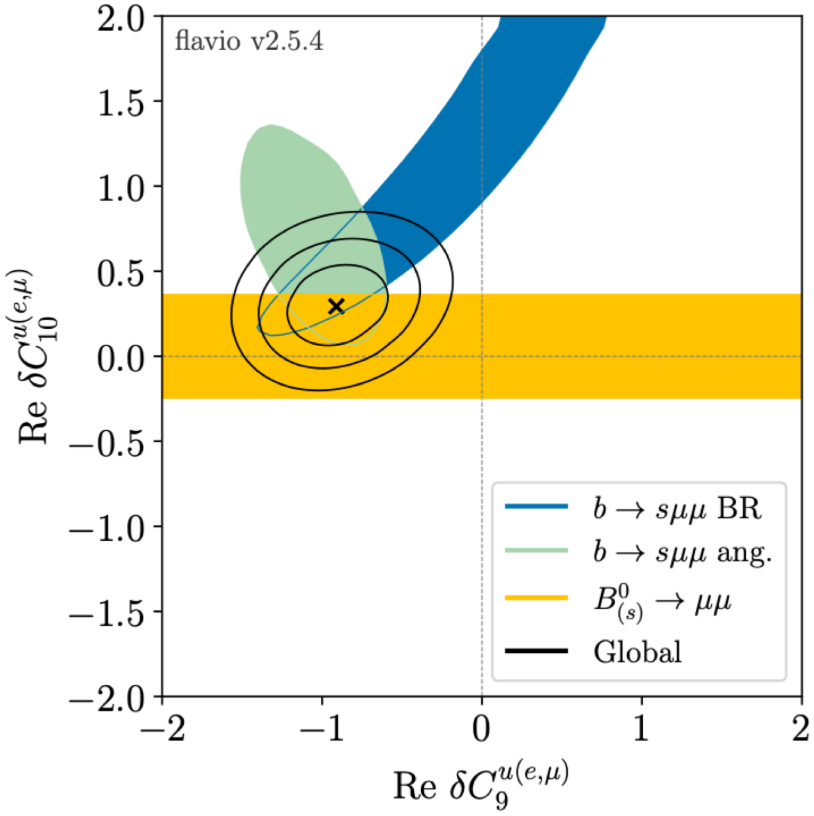

EXAMPLE

Guadagnoli, Normand, Simula, LV, JHEP '23 [2308.00034]

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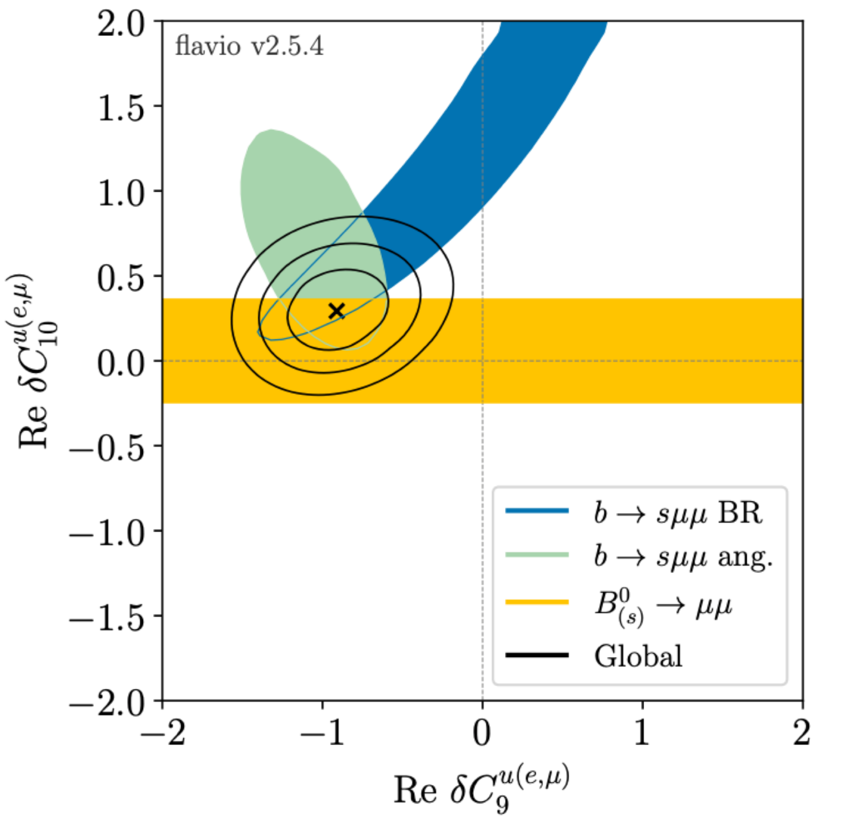

EXAMPLE

***REMARK*: a complete calculation of non-local FFs may, or may not, show that the NP shifts previously shown, in particular those involving C_9, are actually due to SM long-distance dynamics !!**

(See also the global analyses in JHEP '23 [2212.10497], PRD '23 [2212.10516] ...)

$B_s \to \mu\mu\gamma$ as a golden channel to study NP

Main ingredients of our sensitivity study:

2. ***Experimental uncertainties:* *we will assume that all the backgrounds are under control, i.e. that their uncertainties will eventually fall safely below the signal yield ("no-background" hypothesis).***

Thus, the Bs → μμγ-signal uncertainty will be dominated by the sheer amount of data collected

(Many effects to be taken into account: efficiencies, optimal choice of $(q_{min})^2$, …)

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Recall that we need to resolve

$$\delta C_9^{(\mu)} / C_9^{(\mu),\mathrm{SM}} \simeq 15\% \;\; !!$$

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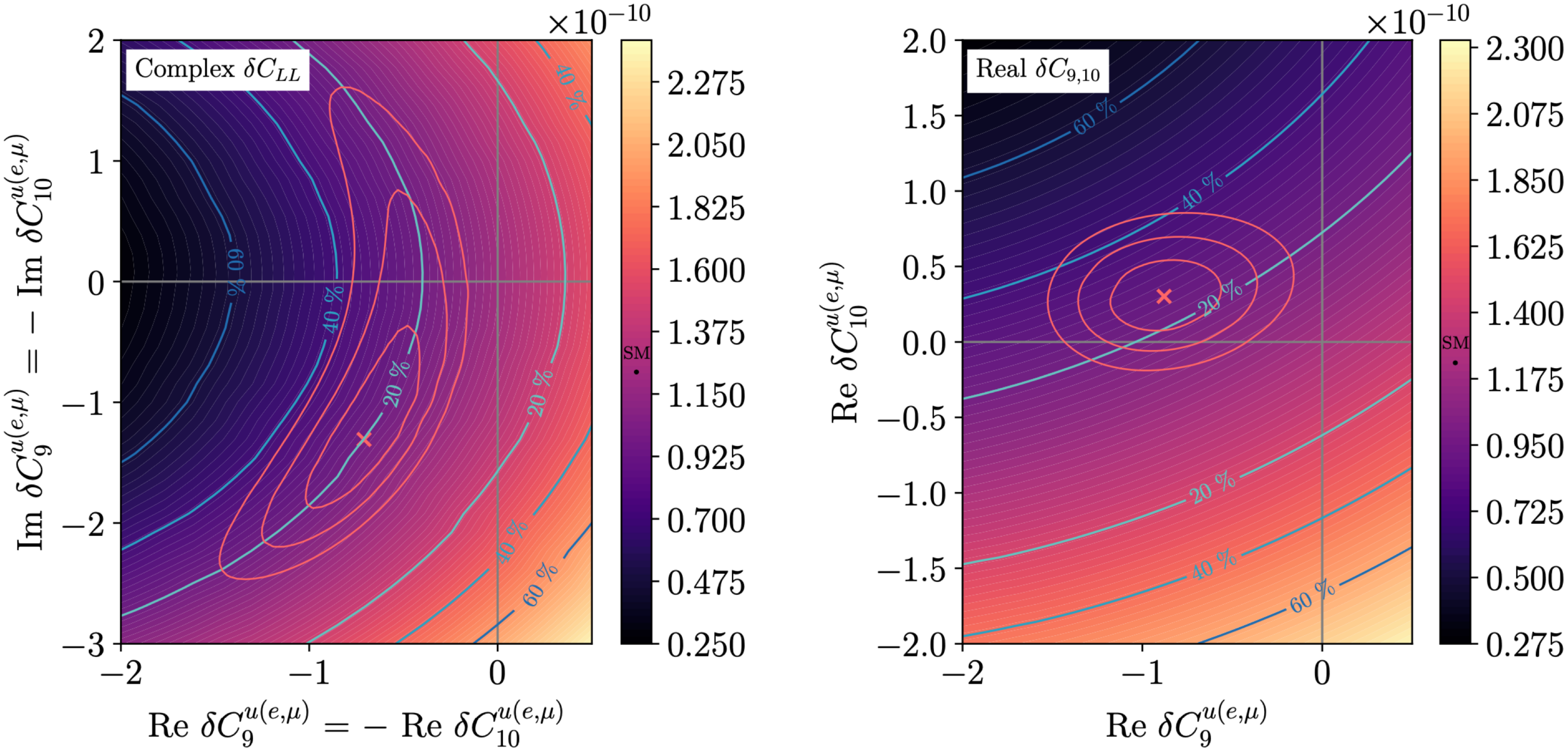
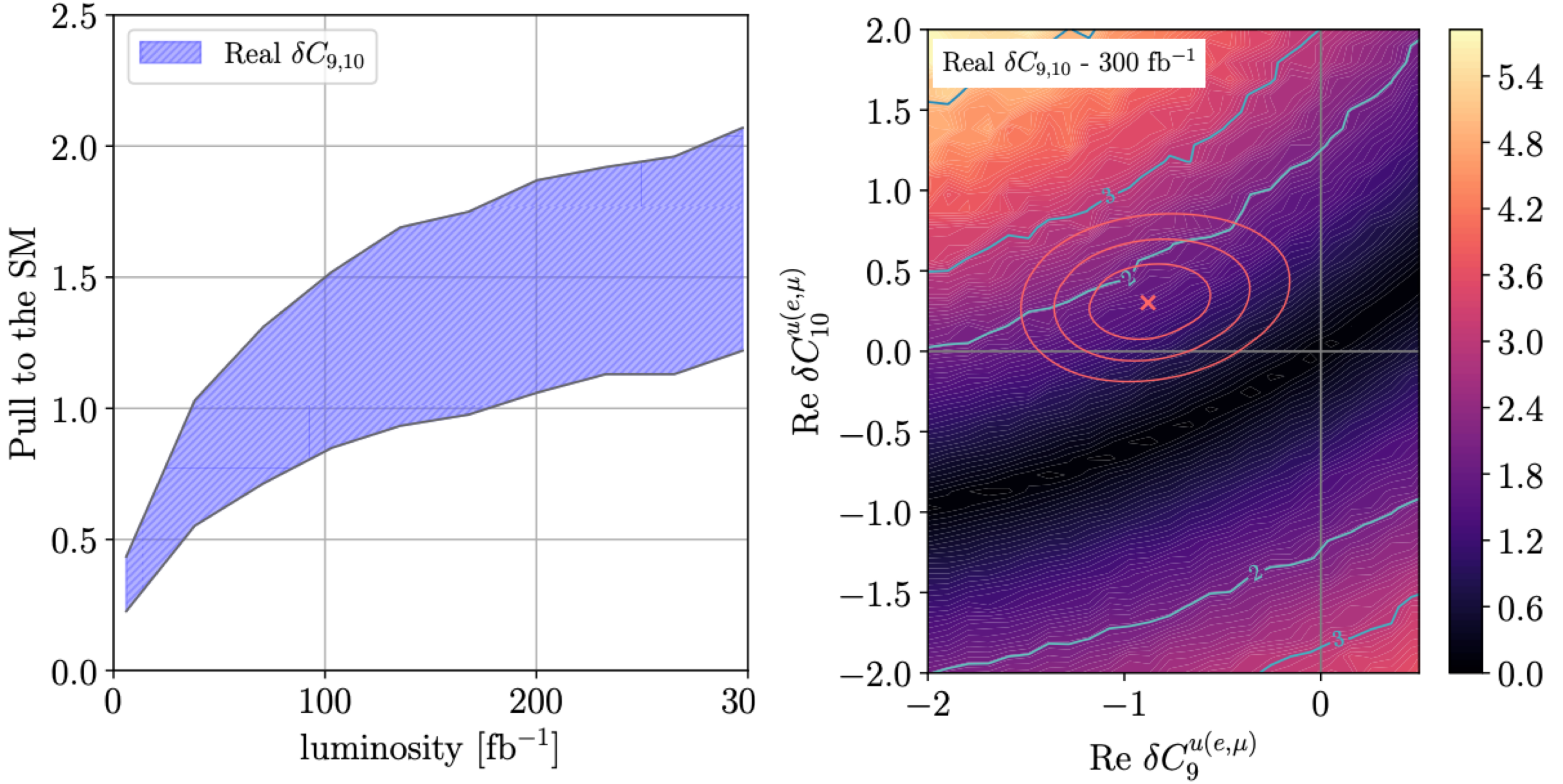


Integrated BR **for two different NP scenarios**

Guadagnoli, Normand, Simula, LV, JHEP '23 [2308.00034]

$B_s \to \mu\mu\gamma$ as a golden channel to study NP



Pull to the SM of the BR **assuming NP in both C_9, C_{10}**

Guadagnoli, Normand, Simula, LV, JHEP '23 [2308.00034]

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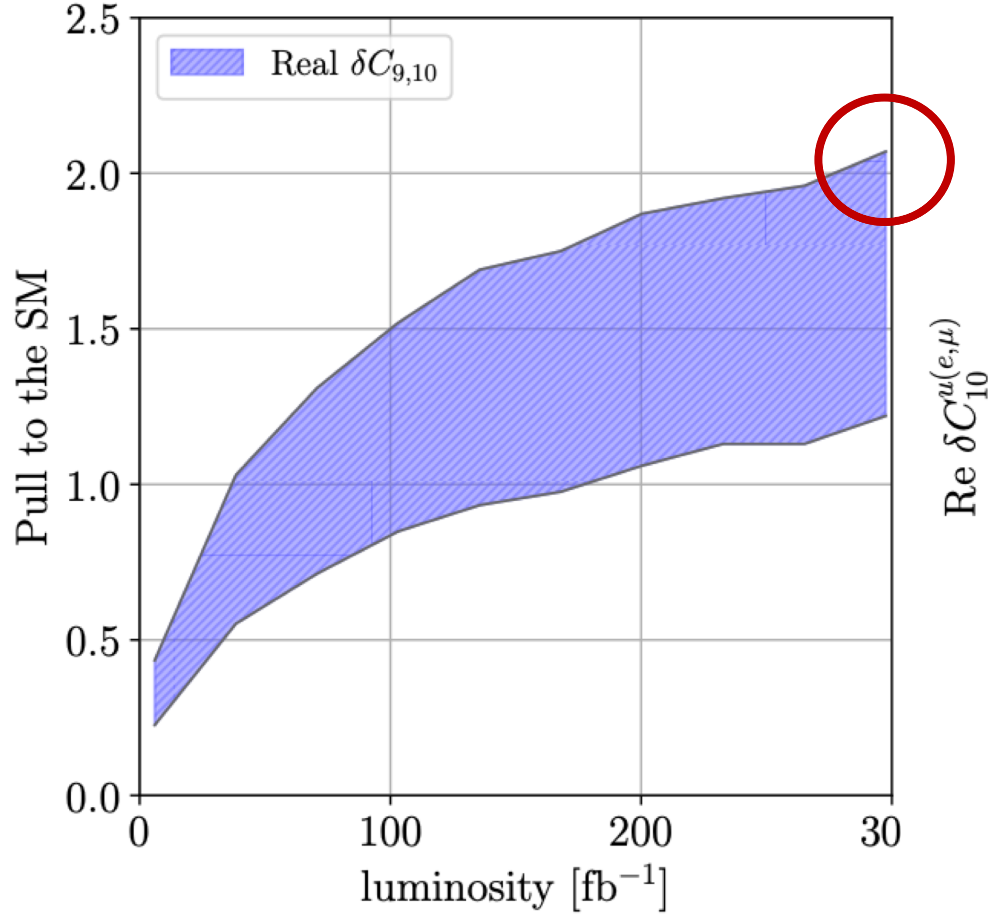

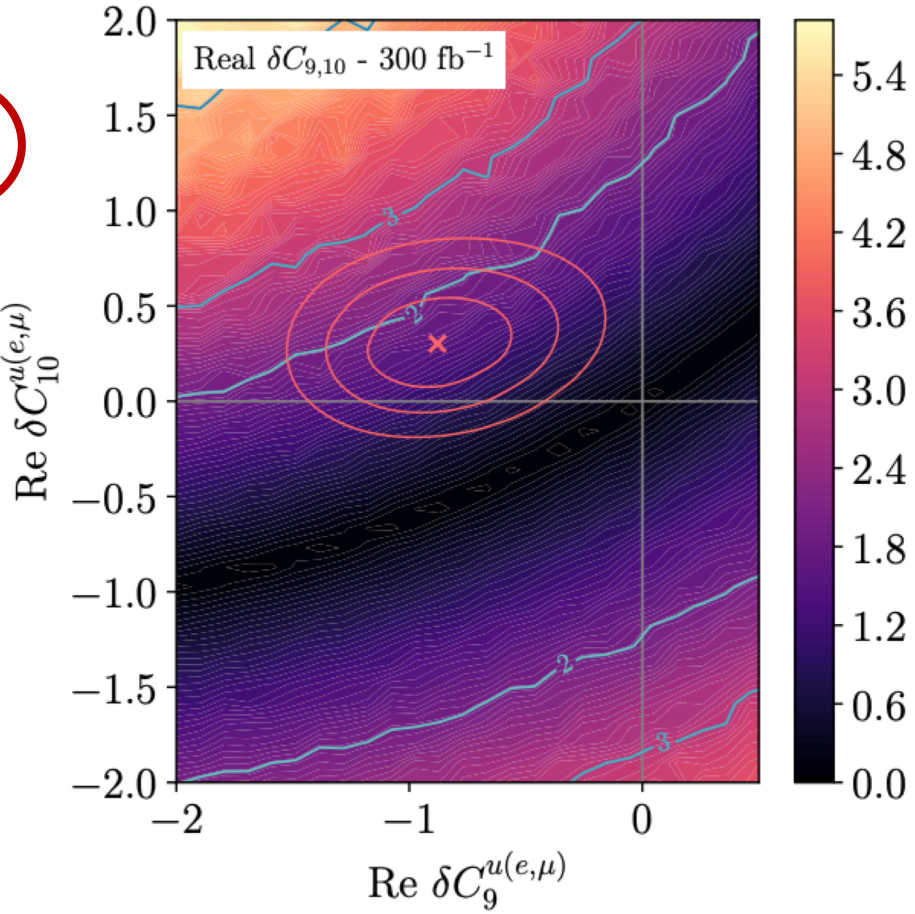

It reaches the 2σ level at the border of the 1σ region for the WC shift preferred by our global fit !

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Guadagnoli, Normand, Simula, LV, JHEP '23 [2308.00034]

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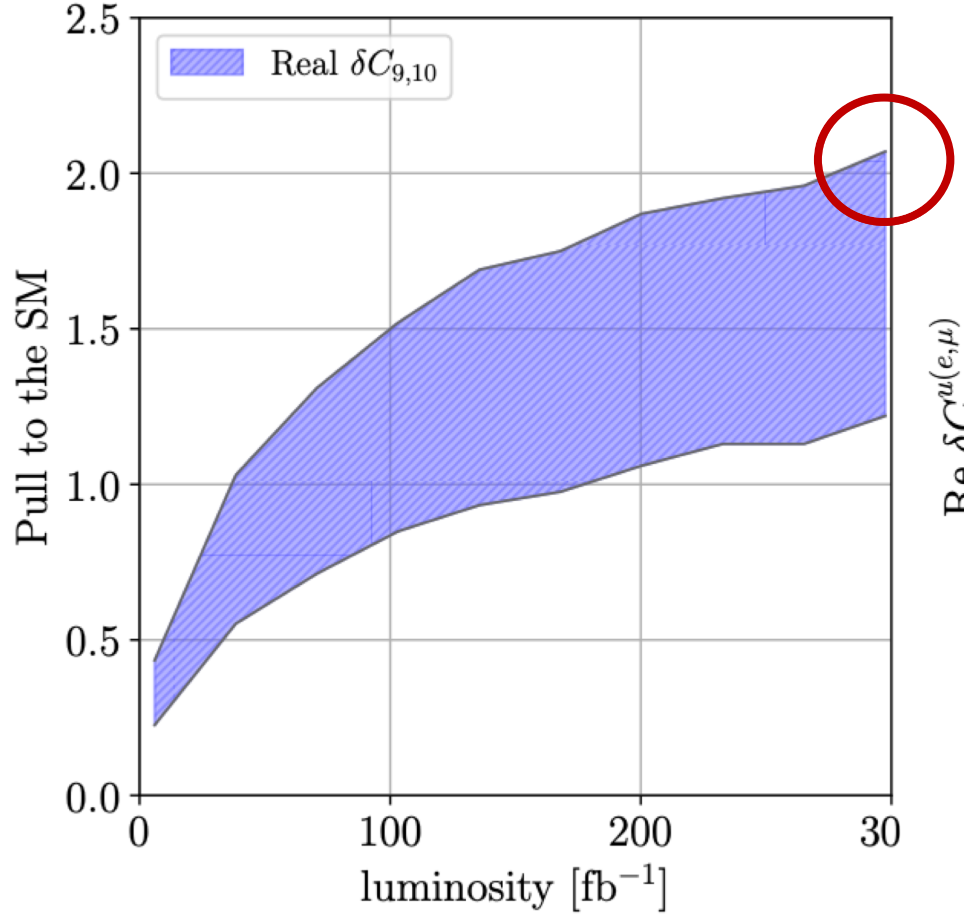

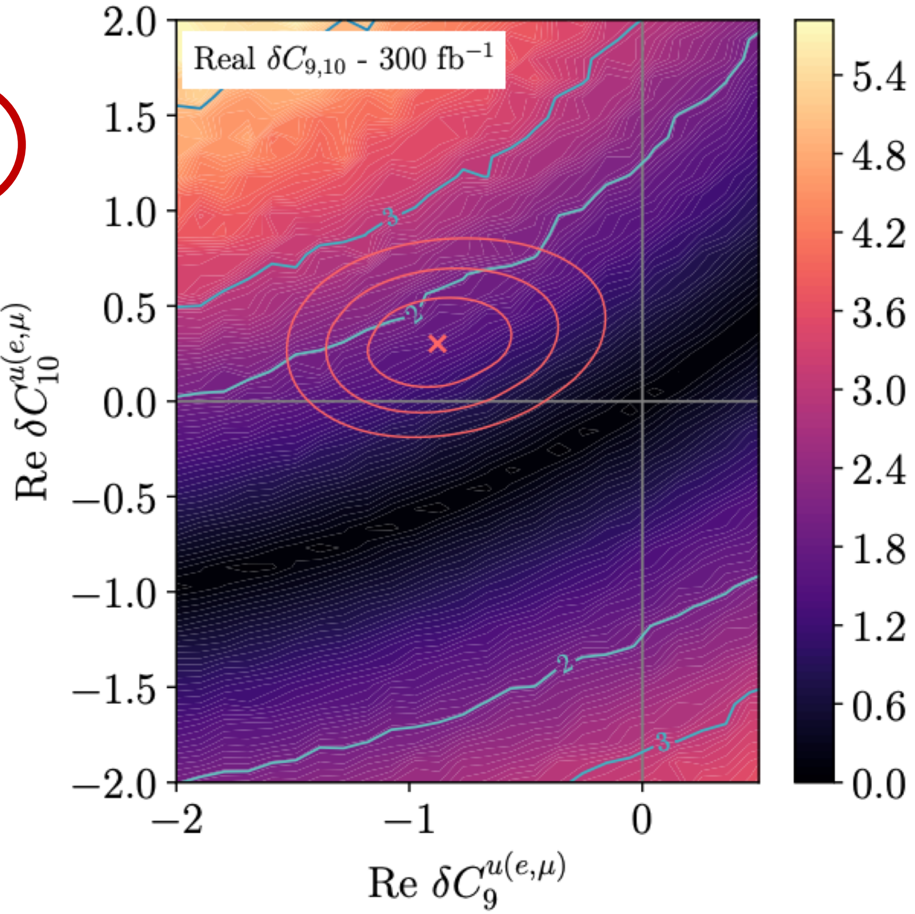

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Methodological issue:
this exercise can be repeated and updated in the future with other FFs determinations (as, for instance, the ETMC results in 2402.03262)

Pull to the SM of the BR **assuming NP in both C_9, C_{10}**

Guadagnoli, Normand, Simula, LV, JHEP '23 [2308.00034]

Conclusions

Radiative-and-leptonic $B_s \rightarrow \mu\mu\gamma$ decay is an important channel to be investigated at present. Huge efforts have been and are being developed by both the theoretical and the experimental communities to have new data! In this talk:

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1. **Study of $B_s \to \mu\mu\gamma$ within the SM:** descrition of a HQET-based procedure to infer the behaviour of the FFs in the Bs-sector starting from LQCD data available for the Ds-sector @ high-q2:
   - **inter-connection with non-leptonic radiative decays (see *e.g.* the determination of the 3-couplings)**
   - **crucial dependence on the LQCD input data (recall the comparison with arXiv:2402.03262)**
   - **possible method for global analyses of all the lattice data available in the future**

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   - **possible method for global analyses of all the lattice data available in the future**

2. **Study of $B_s \to \mu\mu\gamma$ beyond the SM:** complementary way to investigate hypothetical New Physics (NP) effects affecting *$b \to s$ quark transitions*
   - ***key issue*: same short-distance effects present in semileptonic neutral-current B decays, while being independent (and free) of the long-distance ones ! Complementary insight on the debate on non-local FFs**
   - **the pull to the SM can reach the *2σ level* at the border of the 1σ region for the WC C_9 shift preferred by our global fit of BRs and angular observables in B \to K(*) decays**
   - **assumption on the exp./th. uncertainties improvable in the future**

THANKS FOR
YOUR ATTENTION!

BACK-UP SLIDES

The "indirect" method to detect radiative-and-leptonic decays

The basic idea is to reconstruct the radiative signal from the non-radiative counterpart, namely

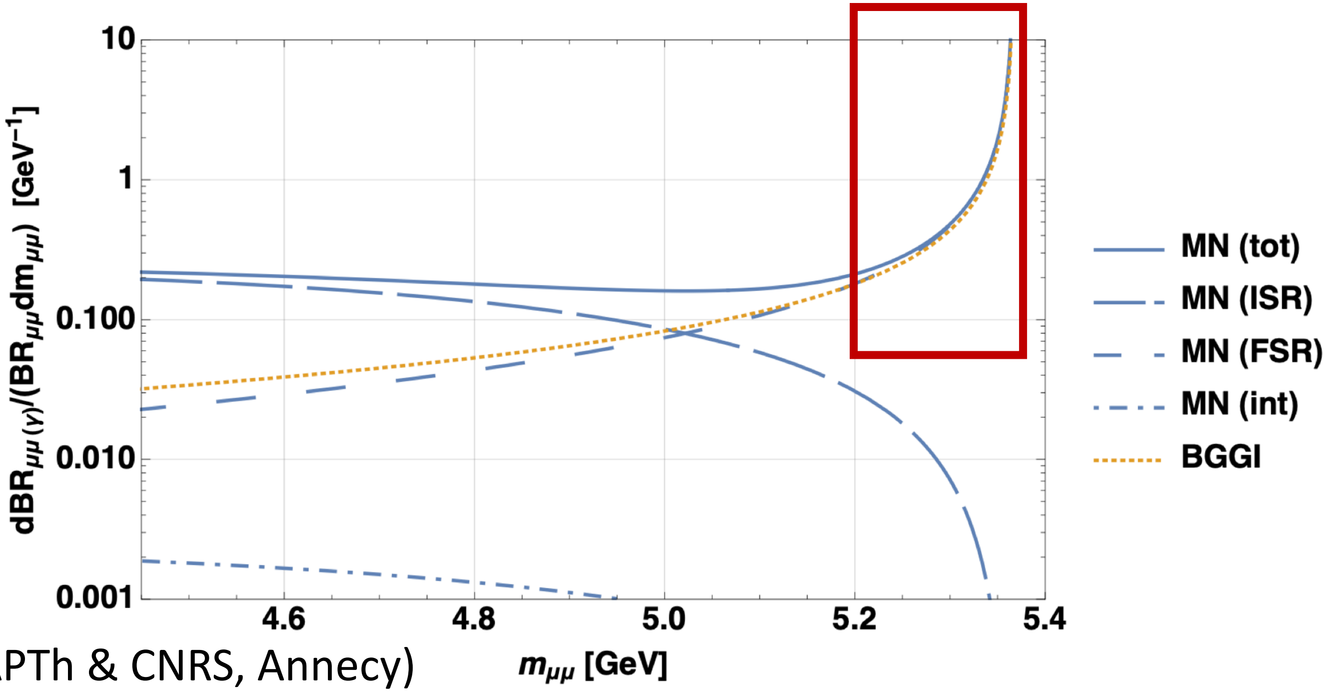
$$B_s^0 \to \mu^+\mu^-\gamma \text{ from } B_s^0 \to \mu^+\mu^-$$

Dettori, Guadagnoli, Reboud, Phys.Lett.B 768 (2017) 163-167

How? Enlarging the dilepton invariant mass below the Bs-peak (it works IF the bkgs are well under control!)

The problem is in other words

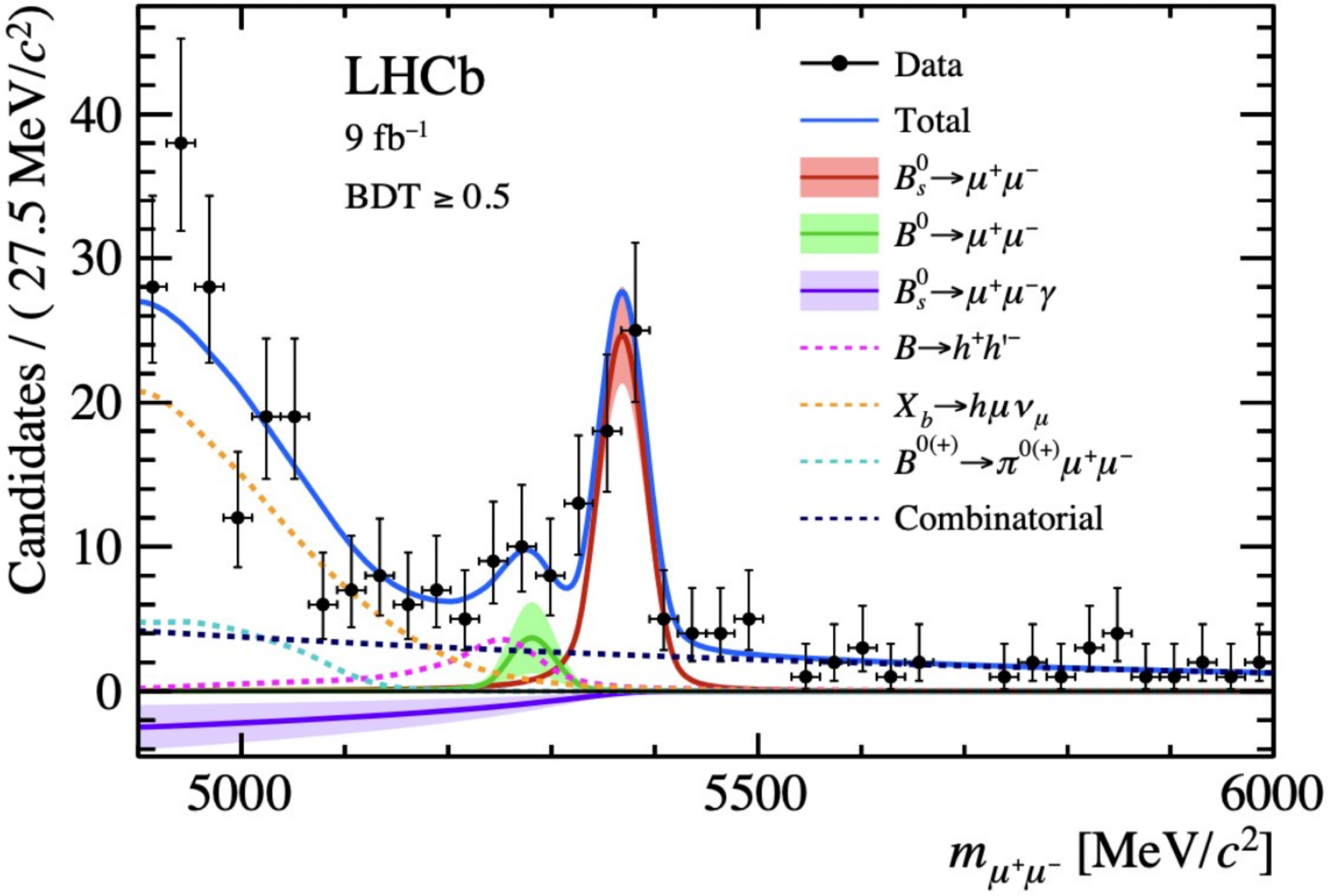
$$\mathcal{B}(B_s^0 \to \mu^+\mu^- + n\gamma) \text{ VS } \mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)$$



For very soft photons, the single-photon component of the former should be equal to the latter!

The "indirect" method to detect radiative-and-leptonic decays

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}} = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} < 2.0 \times 10^{-9}$$



(from LHCb-PAPER-2021-007, LHCb-PAPER-2021-008)

Some pros:

i) No recontruction of the photon, whose efficieny is inherently small

ii) Measur. at high-q2, which is the best region for Lattice QCD and is also the region least affected by resonances

iii) Sensitivity to C9, C10

Some cons:

i) Signal as a «shoulder», i.e. requires reliable estimation of all other «shoulders»

ii) Difficult below (4.2 GeV)^2

iii) Mass resolution crucial !!

Relevant data for $b \to s$ global fits

$b \to s\mu^+\mu^-$ BR obs.
$\left\langle \frac{d\mathcal{B}}{dq^2} \right\rangle (B^+ \to K^{(*)}\mu\mu)$
$\left\langle \frac{d\mathcal{B}}{dq^2} \right\rangle (B_0 \to K\mu\mu)$
$\left\langle \frac{d\mathcal{B}}{dq^2} \right\rangle (B_s \to \phi\mu\mu)$
$\left\langle \frac{d\mathcal{B}}{dq^2} \right\rangle (B_0 \to K^*\mu\mu)$
$\langle \mathcal{B} \rangle (B \to X_s\mu\mu)$
$b \to s\mu^+\mu^-$ angular and CPV obs.
$\langle F_L, P_1, P'_{4,5}, A_{\rm FB} \rangle (B_0 \to K^*\mu^+\mu^-)$
$\langle F_L, P_{1,2}, P'_{4,5} \rangle (B^+ \to K^{*+}\mu^+\mu^-)$
$\langle F_L, S_{3,4,7} \rangle (B_s \to \phi\mu\mu)$
$A_{3-9}(B_0 \to K^*\mu^+\mu^-)$

R_{K/K^*}
$\mathcal{B}(B_{d,s} \to \mu\mu)$
$b \to s\gamma$ obs.
$\langle \mathcal{B}, A_{CP} \rangle (B \to X_s\gamma)$
$\mathcal{B}(B^0 \to K^{*0}\gamma)/\mathcal{B}(B_s^0 \to \phi\gamma)$
$\mathcal{B}(B \to K^*\gamma)$
$\mathcal{B}(B_s^0 \to \phi\gamma)$
$A_{\Delta\Gamma}, S(B_s^0 \to \phi\gamma)$
$S_{K^{*0}\gamma}$

Disappearance of R(K) and R(K*) anomalies

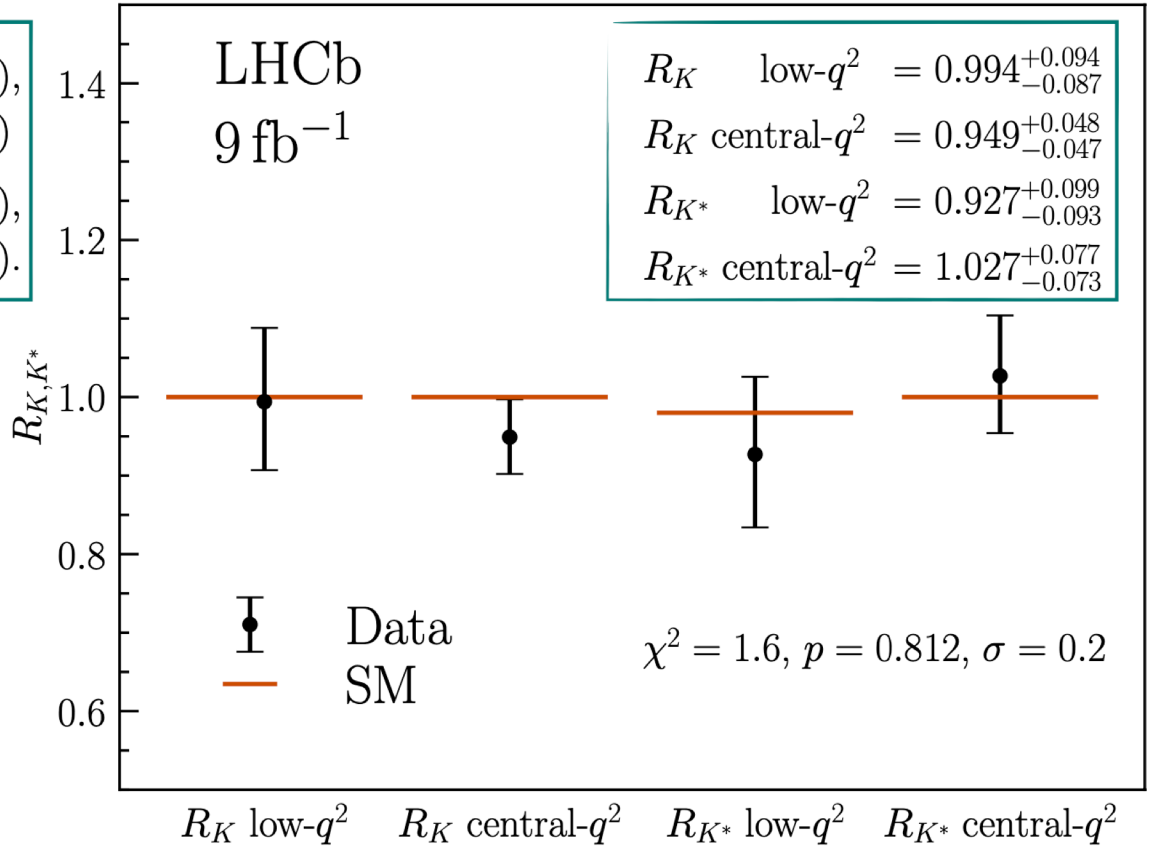
Analysis: results

Results

$$\text{low-}q^2 \begin{cases} R_K = 0.994\ ^{+0.090}_{-0.082}\ (\text{stat})\ ^{+0.027}_{-0.029}\ (\text{syst}), \\ R_{K^*} = 0.927\ ^{+0.093}_{-0.087}\ (\text{stat})\ ^{+0.034}_{-0.033}\ (\text{syst}) \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949\ ^{+0.042}_{-0.041}\ (\text{stat})\ ^{+0.023}_{-0.023}\ (\text{syst}), \\ R_{K^*} = 1.027\ ^{+0.072}_{-0.068}\ (\text{stat})\ ^{+0.027}_{-0.027}\ (\text{syst}). \end{cases}$$

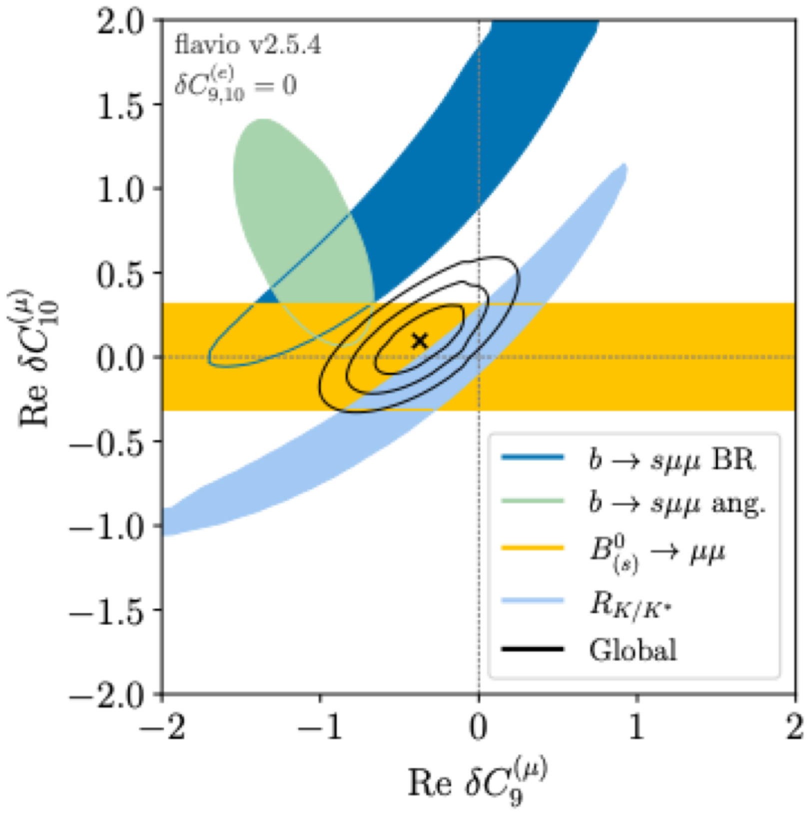
- Most precise and accurate LFU test in $b \to s\ell\ell$ transition
- Compatible with SM with a simple χ^2 test on 4 measurement at 0.2 σ

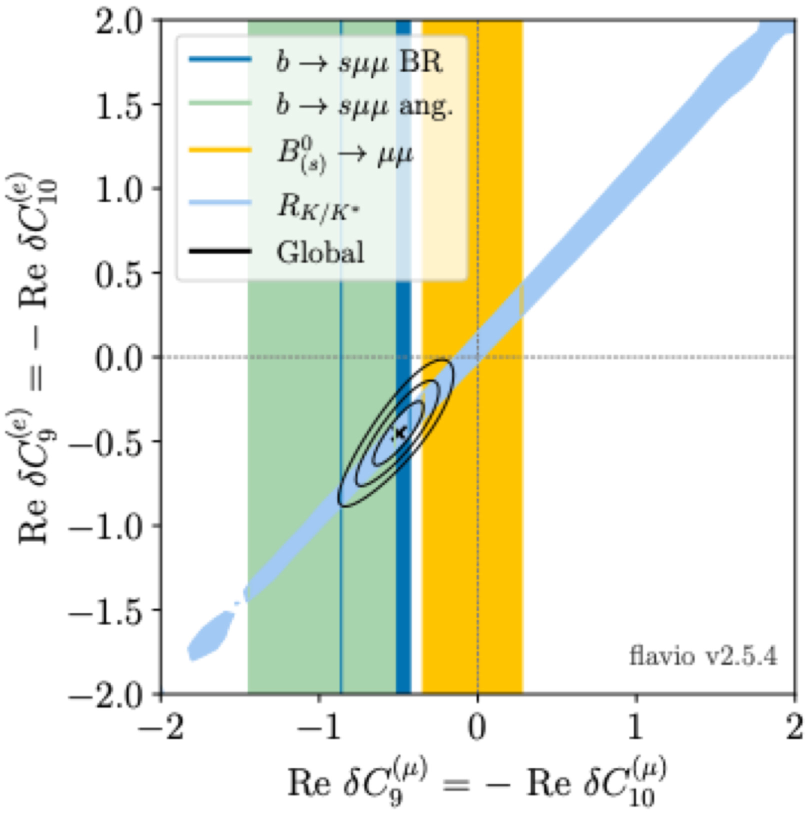


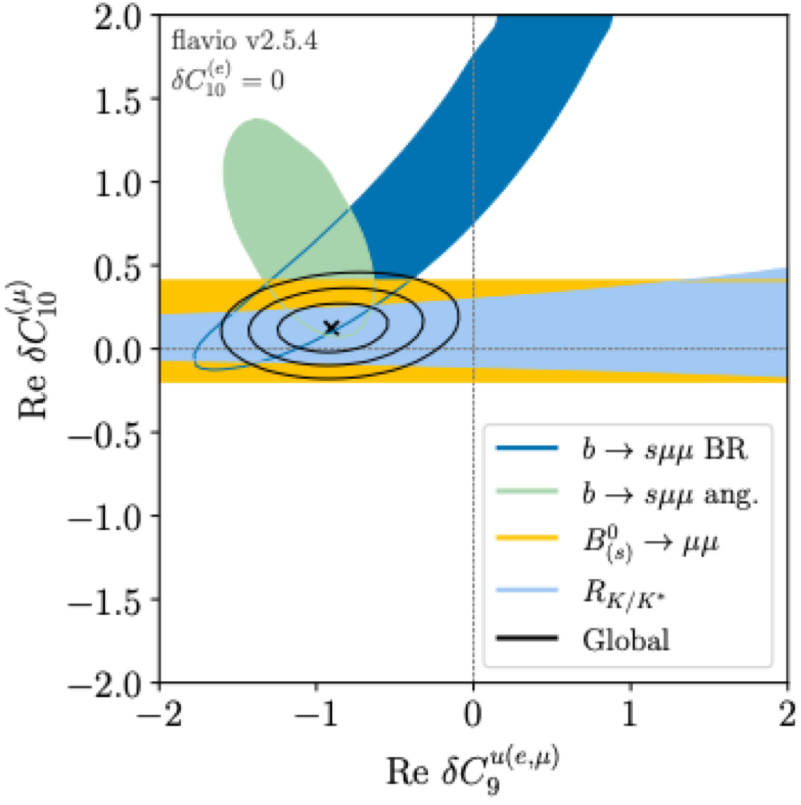
Renato Quagliani — LHC Seminar, CERN — 49

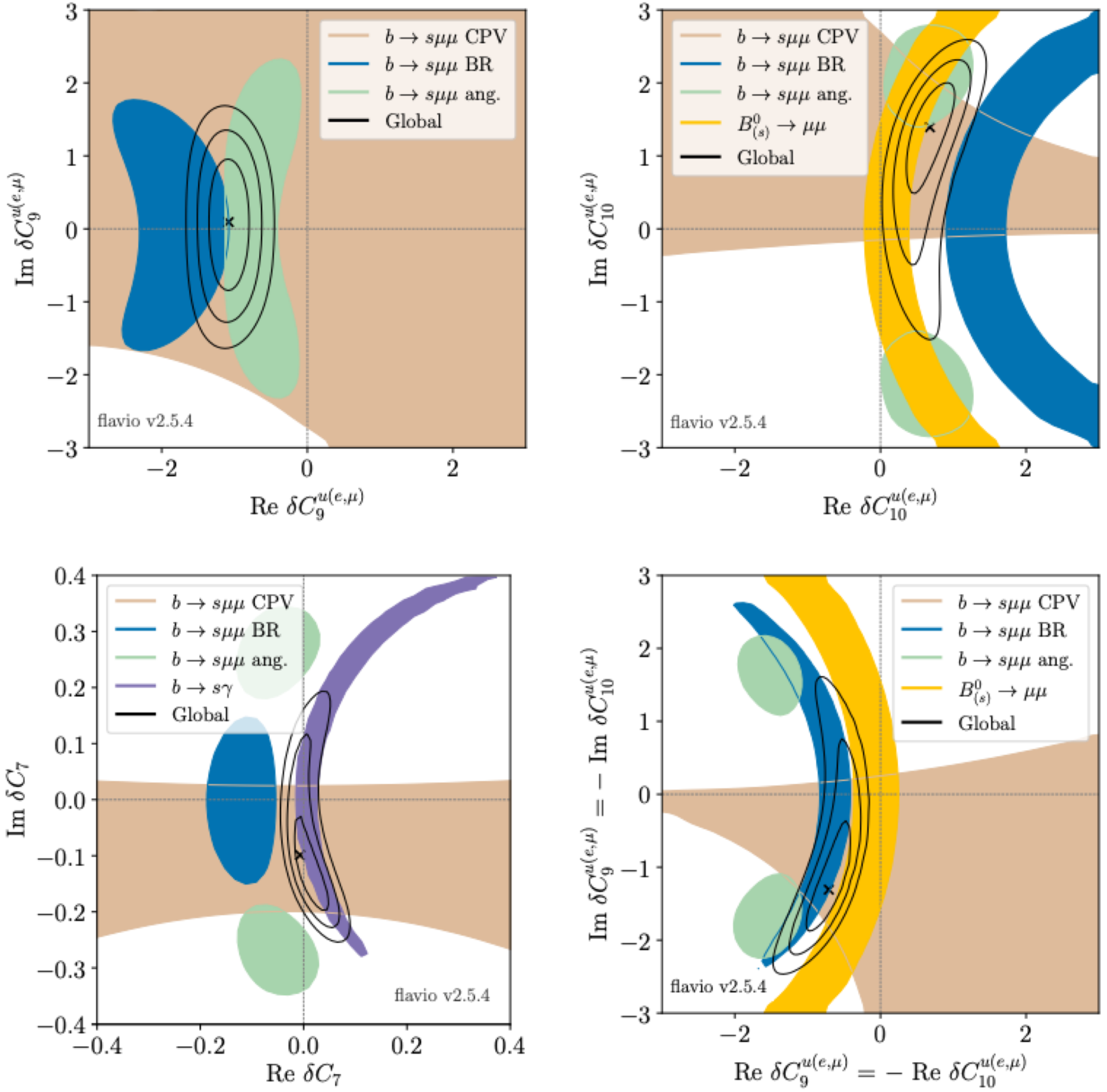
R. Quagliani's talk @ CERN, December the 20th

Other plots concerning fits to the WCs








$b \to s\mu\mu$ CPV
$b \to s\mu\mu$ BR
$b \to s\mu\mu$ ang.
Global
flavio v2.5.4
Re $\delta C_9^{u(e,\mu)}$
Im $\delta C_9^{u(e,\mu)}$
3
2
1
0
−1
−2
−3
−2
0
2
$b \to s\mu\mu$ CPV
$b \to s\mu\mu$ BR
$b \to s\mu\mu$ ang.
$B^0_{(s)} \to \mu\mu$
Global
flavio v2.5.4
Re $\delta C_{10}^{u(e,\mu)}$
Im $\delta C_{10}^{u(e,\mu)}$
$b \to s\mu\mu$ CPV
$b \to s\mu\mu$ BR
$b \to s\mu\mu$ ang.
$b \to s\gamma$
Global
flavio v2.5.4
Re δC_7
Im δC_7
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
0.2
$b \to s\mu\mu$ CPV
$b \to s\mu\mu$ BR
$b \to s\mu\mu$ ang.
$B^0_{(s)} \to \mu\mu$
Global
flavio v2.5.4
Re $\delta C_9^{u(e,\mu)} = -$ Re $\delta C_{10}^{u(e,\mu)}$
Im $\delta C_9^{u(e,\mu)} = -$ Im $\delta C_{10}^{u(e,\mu)}$

Connection with b → c ?

- $C_9^{\text{univ.}}$ of the correct size can be generated through RGE effects
  [**Bobeth-Haisch, 2011**][**Crivellin *et al.*, 2018**][**Aebischer *et al.*, 2019**]

Diego Guadagnoli @ NFLF Workshop 2023, Pisa

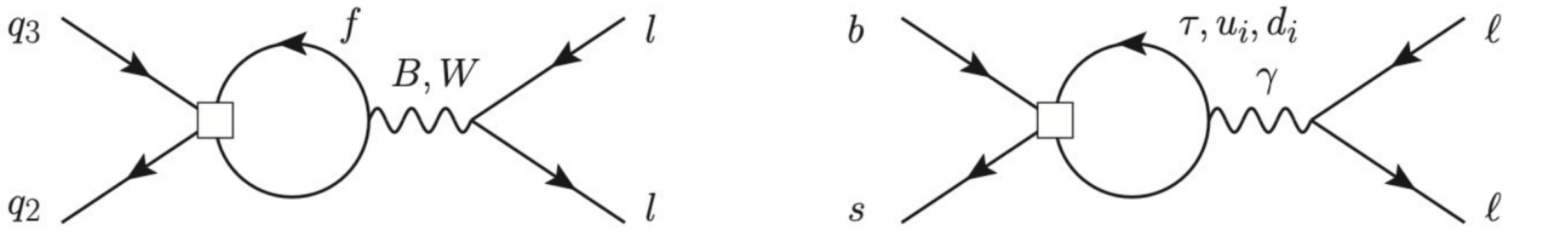


Figure 3: Diagrams inducing a contribution to C_9 through RG running above (left panel) and below (right panel) the EW scale. A sizeable contribution to C_9 is obtained when $f = u_{1,2}, d_{1,2,3}$ or l_3, see text for details.

$$2\mathcal{N}\, C_9^{bs\ell_i\ell_i} = [C_{qe}]_{23ii} + [C_{lq}^{(1)}]_{ii23} + [C_{lq}^{(3)}]_{ii23} - \zeta c_Z \,,$$

$$2\mathcal{N}\, C_{10}^{bs\ell_i\ell_i} = [C_{qe}]_{23ii} - [C_{lq}^{(1)}]_{ii23} - [C_{lq}^{(3)}]_{ii23} + c_Z \,,$$

$$[O_{qe}]_{23ii} = (\bar{q}_2\gamma_\mu q_3)(\bar{e}_i\gamma^\mu e_i)\,,$$

$$[O_{lq}^{(1)}]_{ii23} = (\bar{l}_i\gamma_\mu l_i)(\bar{q}_2\gamma^\mu q_3)\,,$$

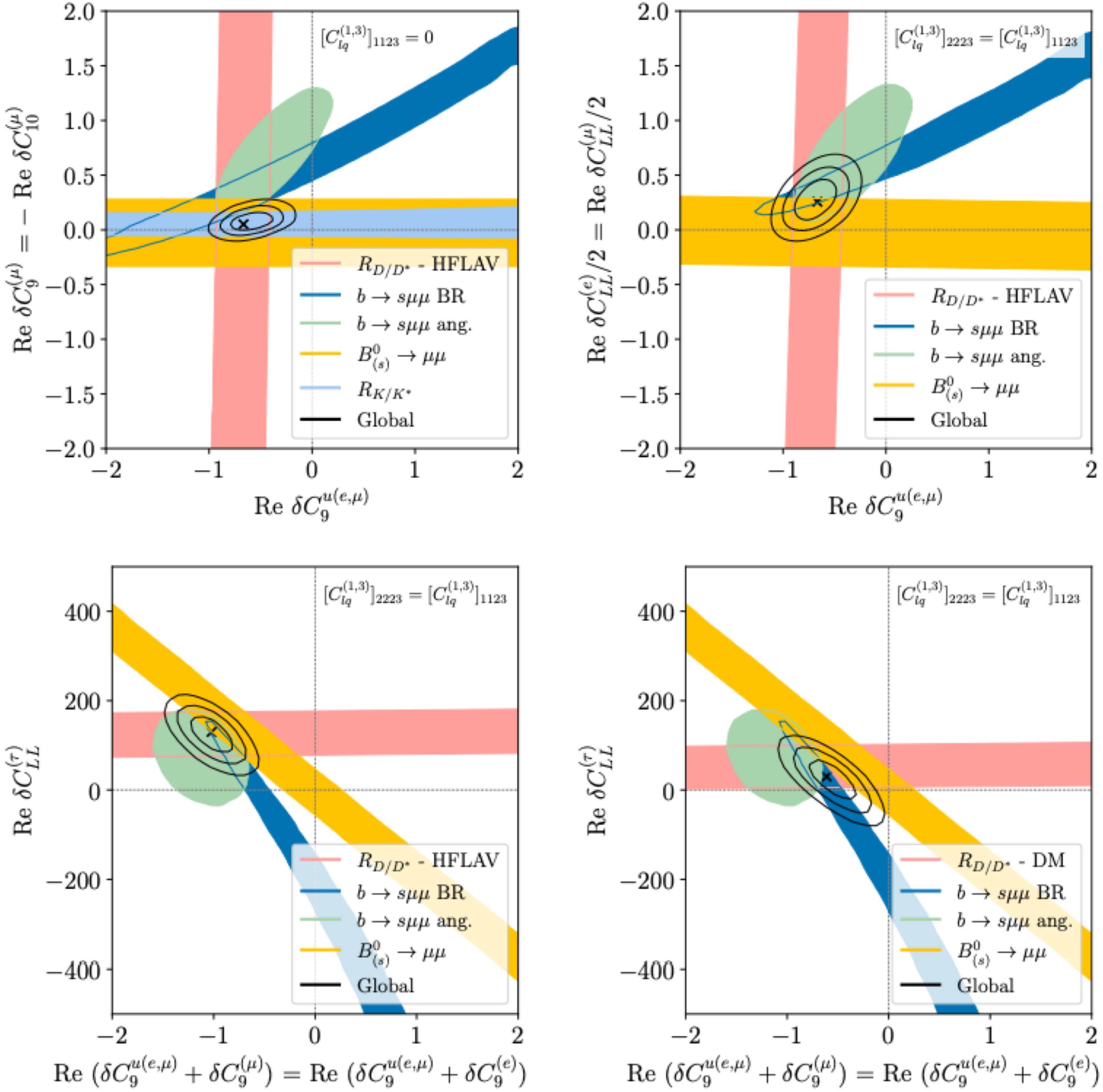
$$[O_{\varphi q}^{(1)}]_{23} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_2\gamma^\mu q_3)\,,$$

$$[O_{lq}^{(3)}]_{ii23} = (\bar{l}_i\gamma_\mu\tau^I l_i)(\bar{q}_2\gamma^\mu\tau^I q_3)\,,$$

$$[O_{\varphi q}^{(3)}]_{23} = (\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_2\gamma^\mu\tau^I q_3)\,,$$

Intriguingly, a large value for $[C_{lq}^{(3)}]_{3323}$, that can explain the hints for LFU violation in charged-current $b \to c$ transitions (R_D and R_{D^*}), also induces a LFU effect in C_9 that goes in the right direction to solve the $b \to s\mu\mu$ anomalies in branching ratios and angular observables.

Jason Aebischer et al., EPJC '20 [arXiv:1903.10434 [hep-ph]]



$[C_{lq}^{(1,3)}]_{1123} = 0$
Re $\delta C_9^{(\mu)} = -$ Re $\delta C_{10}^{(\mu)}$
Re $\delta C_9^{u(e,\mu)}$
R_{D/D^*} - HFLAV
$b \to s\mu\mu$ BR
$b \to s\mu\mu$ ang.
$B^0_{(s)} \to \mu\mu$
R_{K/K^*}
Global
$[C_{lq}^{(1,3)}]_{2223} = [C_{lq}^{(1,3)}]_{1123}$
Re $\delta C_{LL}^{(e)}/2 =$ Re $\delta C_{LL}^{(\mu)}/2$
Re $\delta C_9^{u(e,\mu)}$
R_{D/D^*} - HFLAV
$b \to s\mu\mu$ BR
$b \to s\mu\mu$ ang.
$B^0_{(s)} \to \mu\mu$
Global
$[C_{lq}^{(1,3)}]_{2223} = [C_{lq}^{(1,3)}]_{1123}$
Re $\delta C_{LL}^{(\tau)}$
Re $(\delta C_9^{u(e,\mu)} + \delta C_9^{(\mu)}) =$ Re $(\delta C_9^{u(e,\mu)} + \delta C_9^{(e)})$
R_{D/D^*} - HFLAV
$b \to s\mu\mu$ BR
$b \to s\mu\mu$ ang.
$B^0_{(s)} \to \mu\mu$
Global
$[C_{lq}^{(1,3)}]_{2223} = [C_{lq}^{(1,3)}]_{1123}$
Re $\delta C_{LL}^{(\tau)}$
Re $(\delta C_9^{u(e,\mu)} + \delta C_9^{(\mu)}) =$ Re $(\delta C_9^{u(e,\mu)} + \delta C_9^{(e)})$
R_{D/D^*} - DM
$b \to s\mu\mu$ BR
$b \to s\mu\mu$ ang.
$B^0_{(s)} \to \mu\mu$
Global

$B \to K^{(*)}\nu\bar{\nu}$ in the SMEFT

Four fermion operators

If the NP contribution is heavy enough, $\Lambda > v$, we can work in the SMEFT

$$\mathcal{L}_{\text{SMEFT}}^{(6)} \supset \frac{1}{\Lambda^2}\Big\{\Big(\mathcal{C}_{lq}^{(1)} + \mathcal{C}_{lq}^{(3)}\Big)_{ij} (\bar{s}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu e_{Lj}) + \Big(\mathcal{C}_{lq}^{(1)} - \mathcal{C}_{lq}^{(3)}\Big)_{ij} (\bar{s}_L\gamma^\mu b_L)(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj})$$
$$+ 2V_{cs}\Big[\mathcal{C}_{lq}^{(3)}\Big]_{ij} (\bar{c}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu \nu_{Lj}) + [\mathcal{C}_{ld}]_{ij} (\bar{s}_R\gamma^\mu b_R)\left[(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj}) + (\bar{e}_{Li}\gamma_\mu e_{Lj})\right] + \text{h.c.}\Big\}$$

Matching to the low-energy NP couplings

$$\delta C_L^{\nu_i\nu_j} = \frac{\pi}{\alpha_{\text{em}}\lambda_t}\frac{v^2}{\Lambda^2}\Big\{\Big[\mathcal{C}_{lq}^{(1)}\Big]_{ij} - \Big[\mathcal{C}_{lq}^{(3)}\Big]_{ij}\Big\}$$

$$\delta C_R^{\nu_i\nu_j} = \frac{\pi}{\alpha_{\text{em}}\lambda_t}\frac{v^2}{\Lambda^2}[\mathcal{C}_{ld}]_{ij}$$

Contributions to $B \to K\nu\bar{\nu}$ will have an impact on observables with charged leptons!