Theory Overview of Rare Decays within the Standard Model

Ludovico Vittorio (University of Rome Sapienza and INFN, Rome)

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SAPIENZA UNIVERSITÀ DI ROMA

INFN ROMA Istituto Nazionale di Fisica Nucleare Sezione di Roma

MUR Ministero dell'Università e della Ricerca

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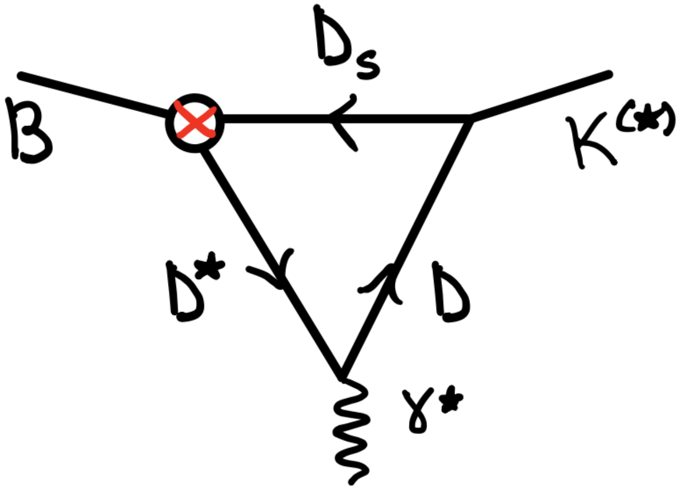

(from PRD 107 (2023) 5, 055036)

Many thanks to G. Martinelli, L. Silvestrini, S. Simula and M. Valli for discussions and suggestions

Introduction: why rare decays are so important

The most apppealing places to look for possible NP effects are rare decays, since rare decays are a manifestation of broken (accidental) symmetries, e.g. of <u>physics beyond the Standard Model</u>

Some general examples:

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Of interest for this talk !

$$\boxed{\begin{aligned} q_i &\rightarrow q_j \ell^+ \ell^-, \\ q_i &\rightarrow q_j \nu \bar{\nu}, \\ q_i &\rightarrow q_j \gamma \end{aligned}}$$

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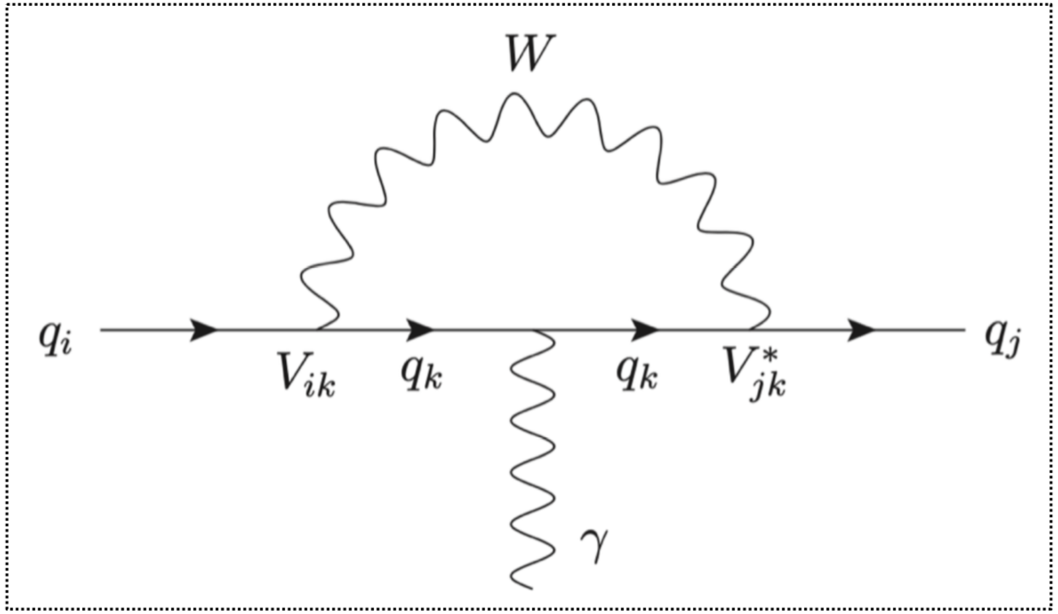

Plan of the talk

a) Semileptonic neutral-current $B_{(s)}$-meson decays

b) Rare radiative-and-leptonic B_s-meson decay

c) Rare semileptonic decays with di-neutrino final states

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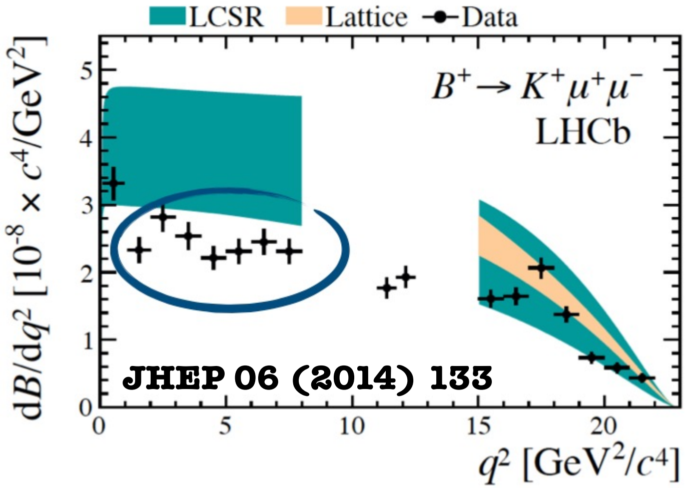
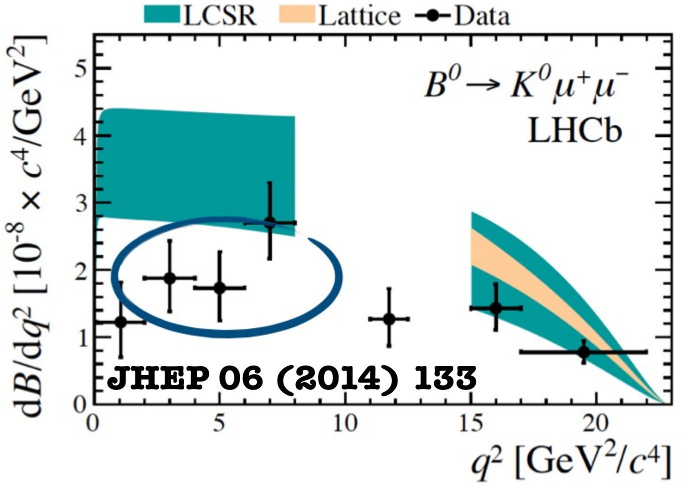
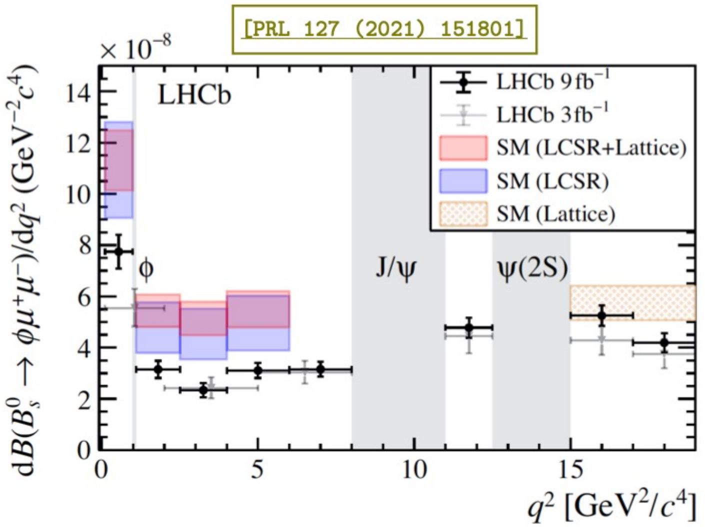
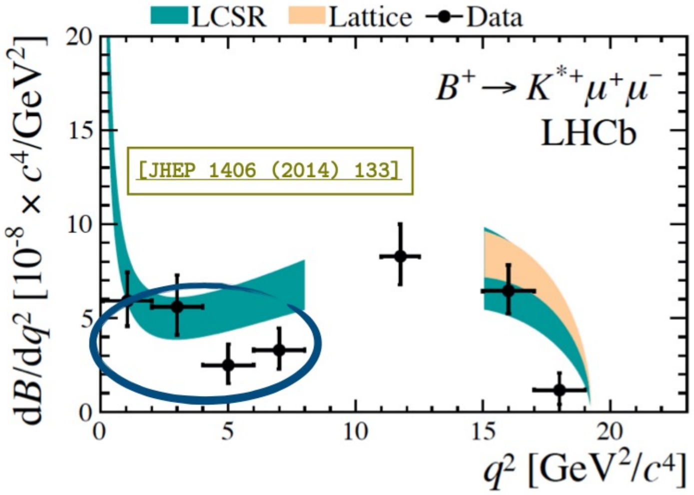
Tensions in BRs and angular observables (?)

Despite the disappearance of the R(K(*)) anomalies (LHCb Coll., PRL 131 (2023) 5, 051803), there are still several discrepancies among theory and experiments in semileptonic neutral-current *B* decays data:









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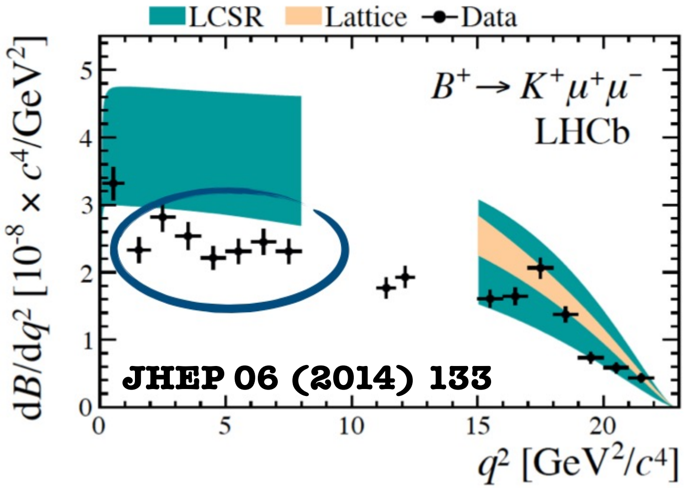
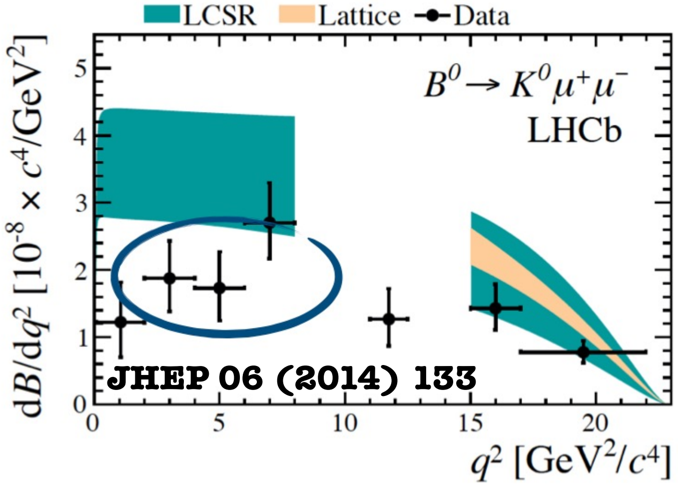
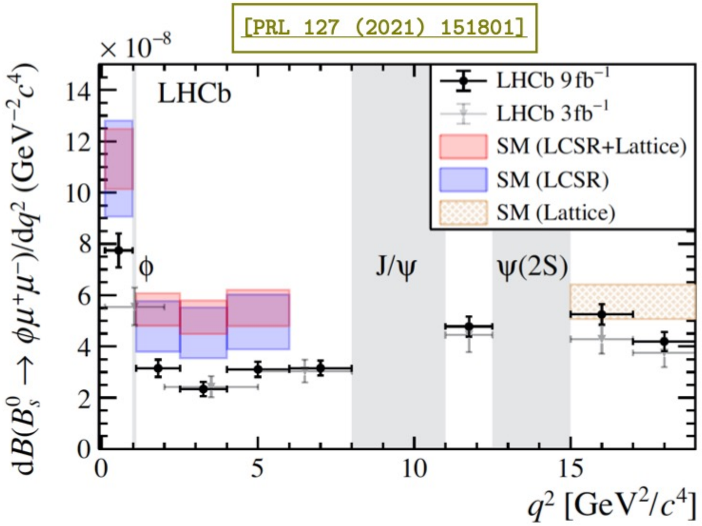
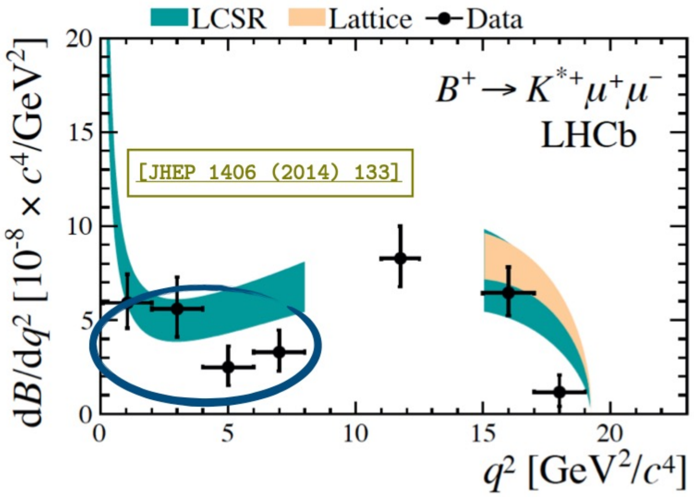




SM expectations seem to be *<u>always above</u>* experimental data …





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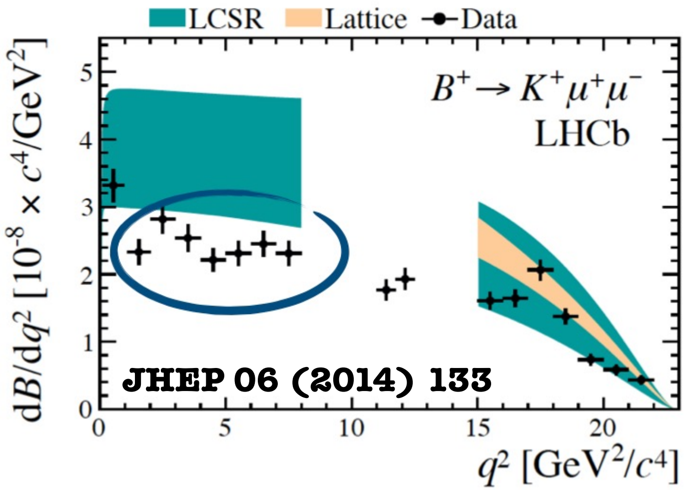

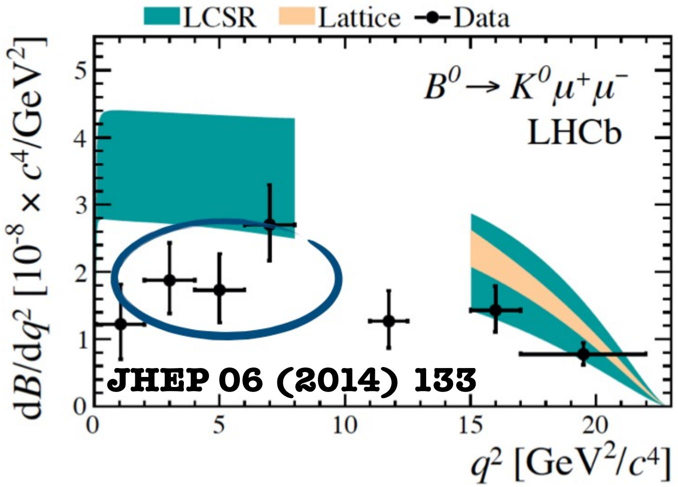

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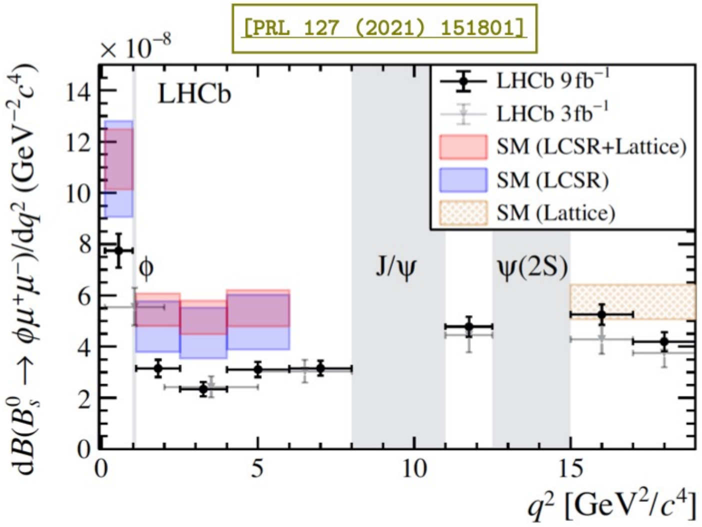

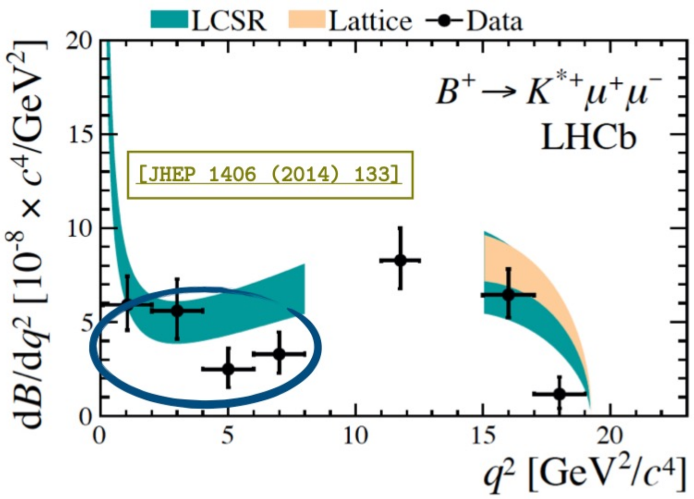

Important debate: is there really NP? Were the hadronic effects treated correctly ?

The central role of hadronic form factors

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

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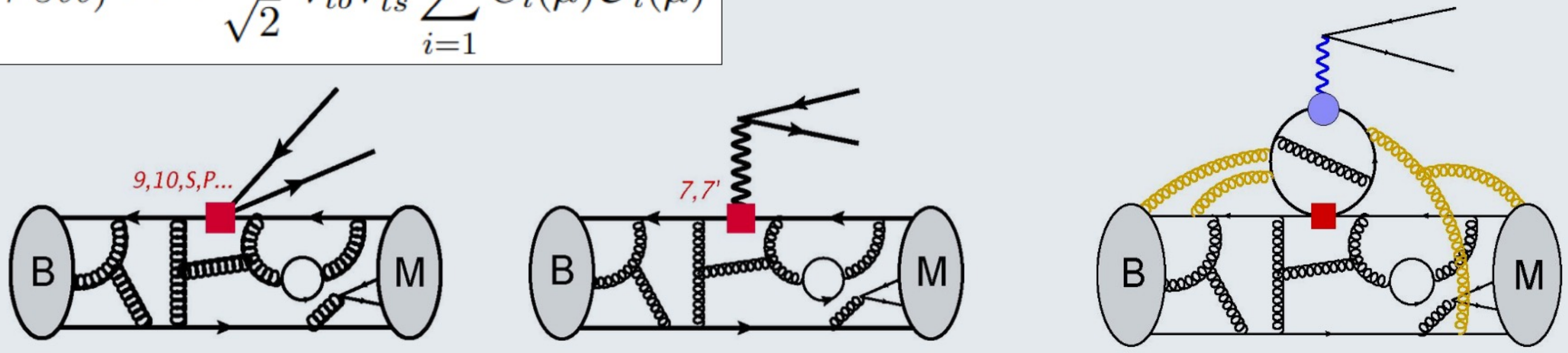

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Non-local form-factors

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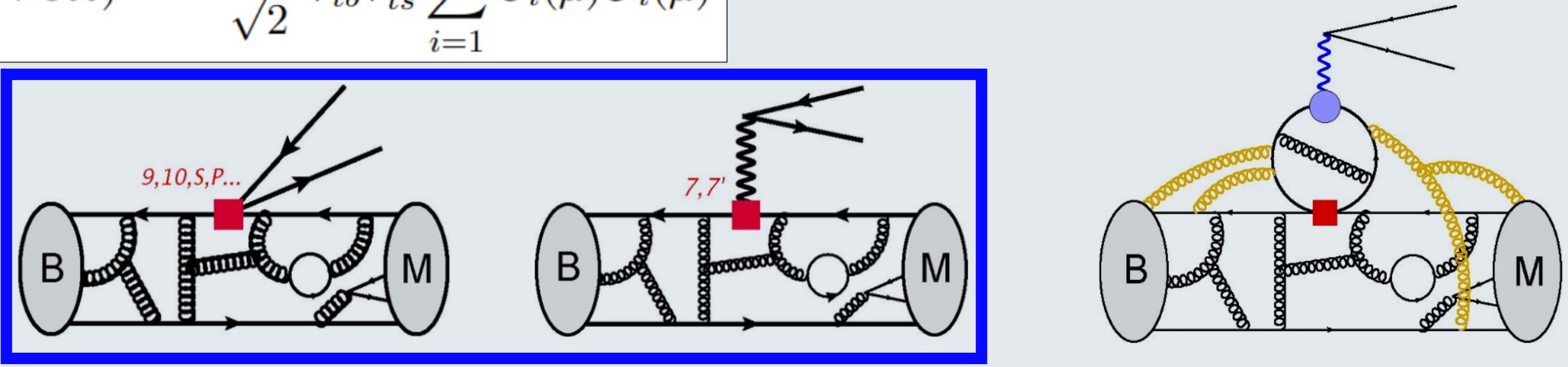

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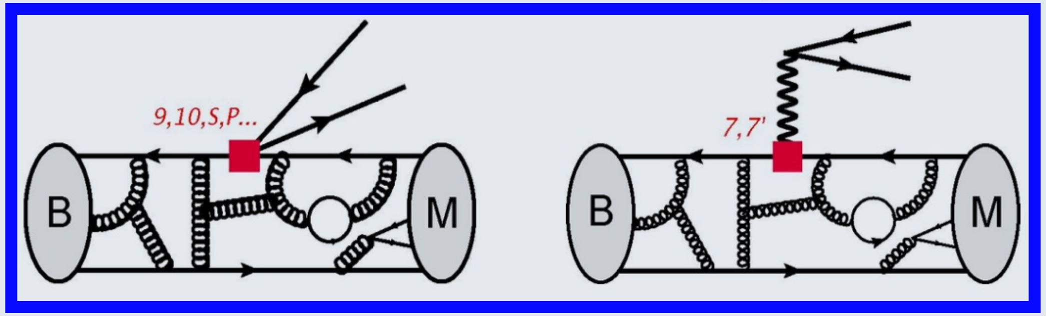

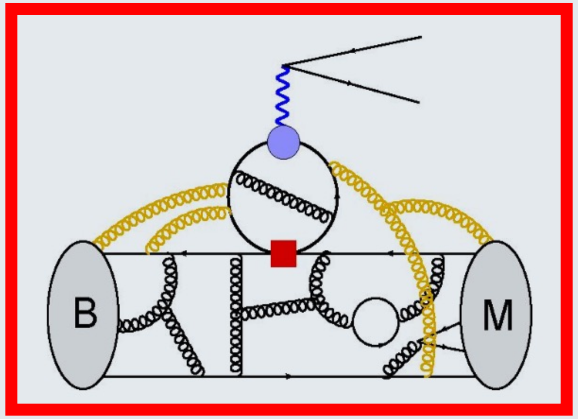

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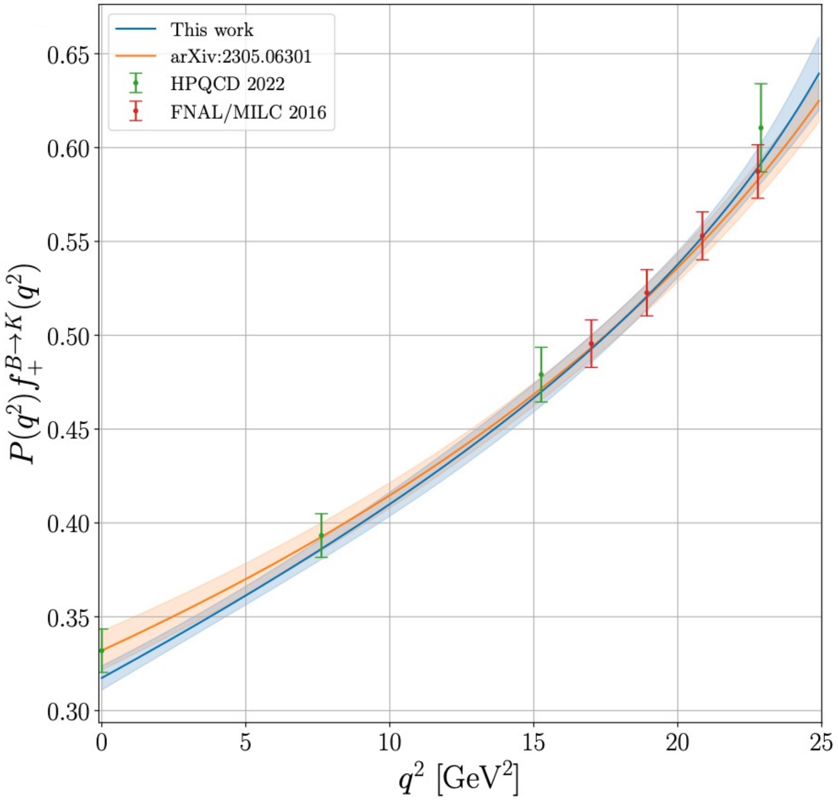
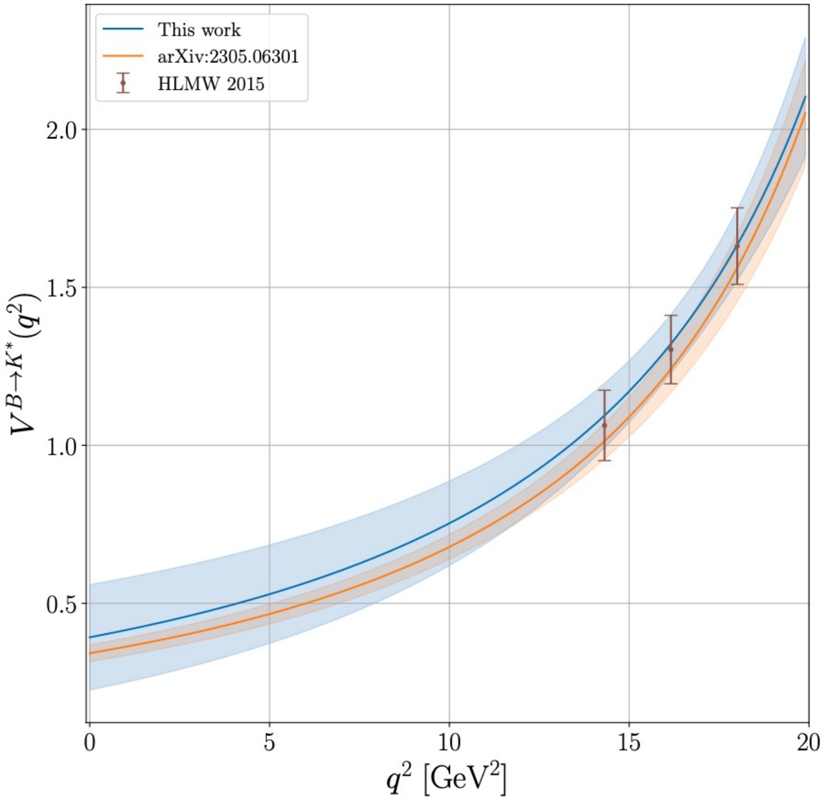
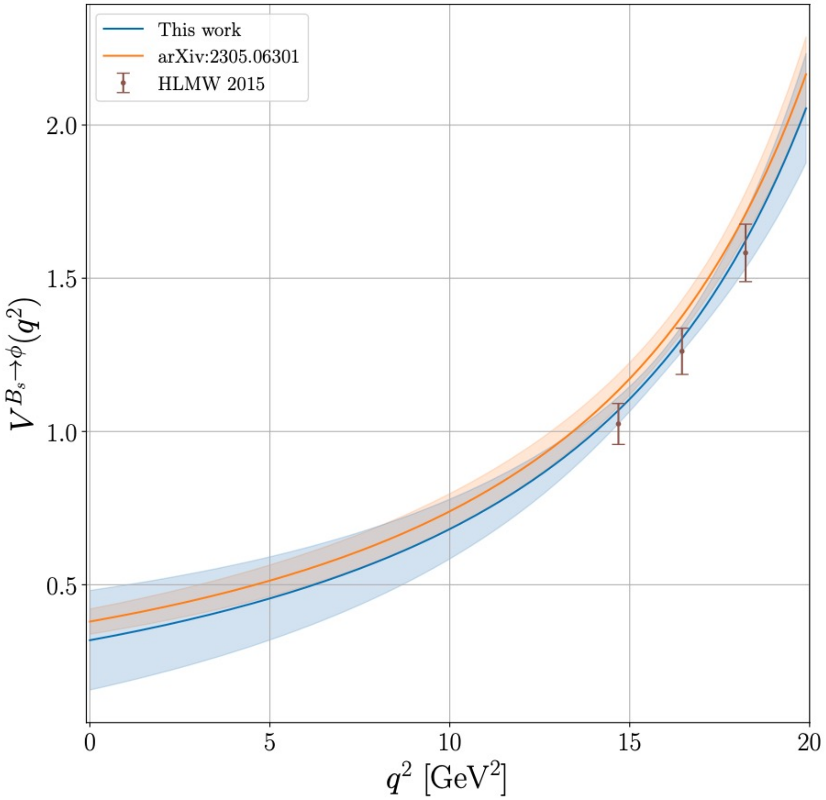
$$i\int d^4x e^{iq\cdot x}\langle P(V)|\mathcal{T}\{j_\mu^{\text{em}}(x),(C_1\mathcal{O}_1 + C_2\mathcal{O}_2)(0)\}B\rangle$$
$$\mathcal{O}_1 = (\bar{s}_L\gamma_\mu T^a q_L)(\bar{q}_L\gamma^\mu T^a b_L),$$
$$\mathcal{O}_2 = (\bar{s}_L\gamma_\mu q_L)(\bar{q}_L\gamma^\mu b_L)$$

Local hadronic form factors

Study of local form factors through the Dispersive Matrix (DM) method:







In preparation with M. Fedele, L. Silvestrini, S. Simula, M. Valli

Available lattice datasets:

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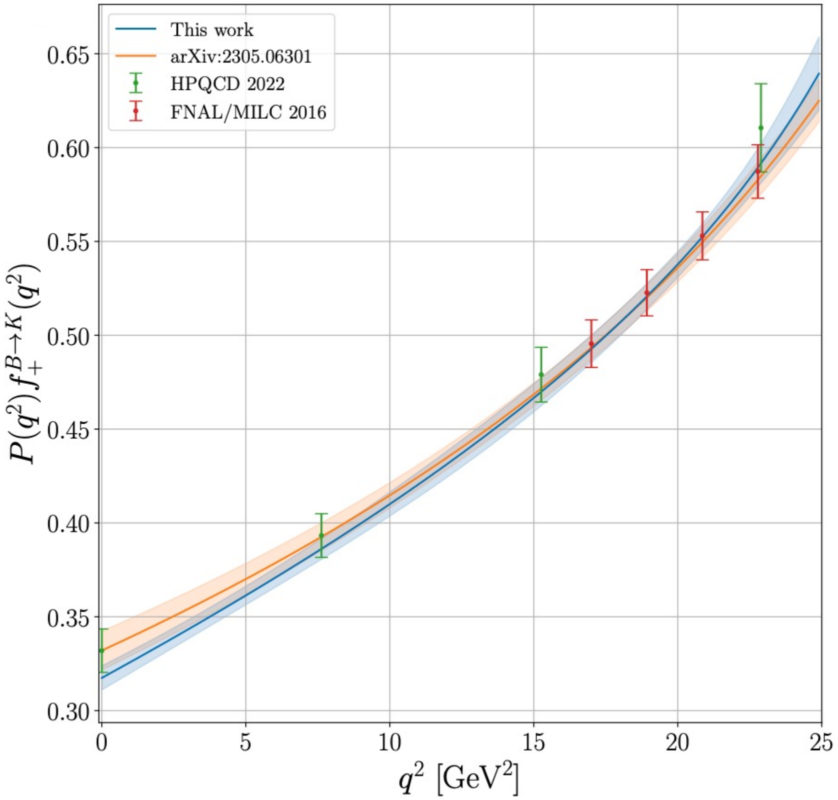

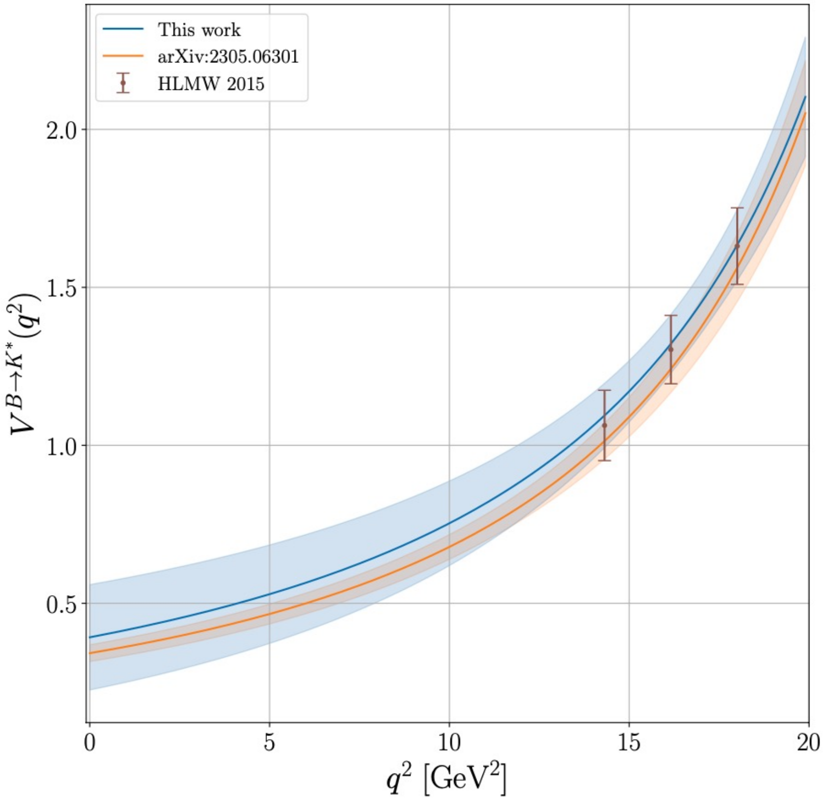

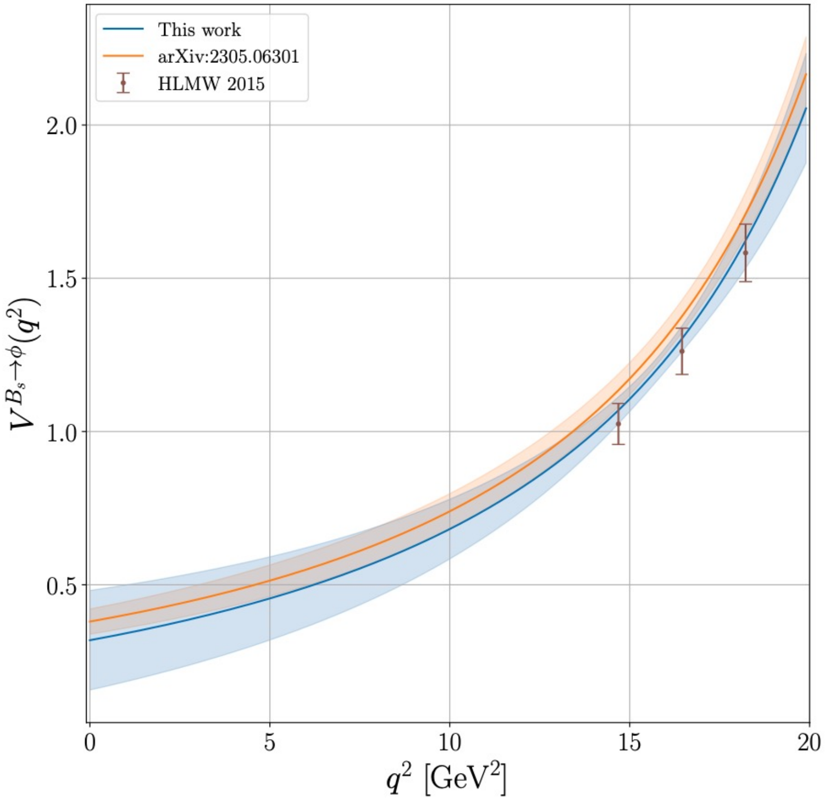

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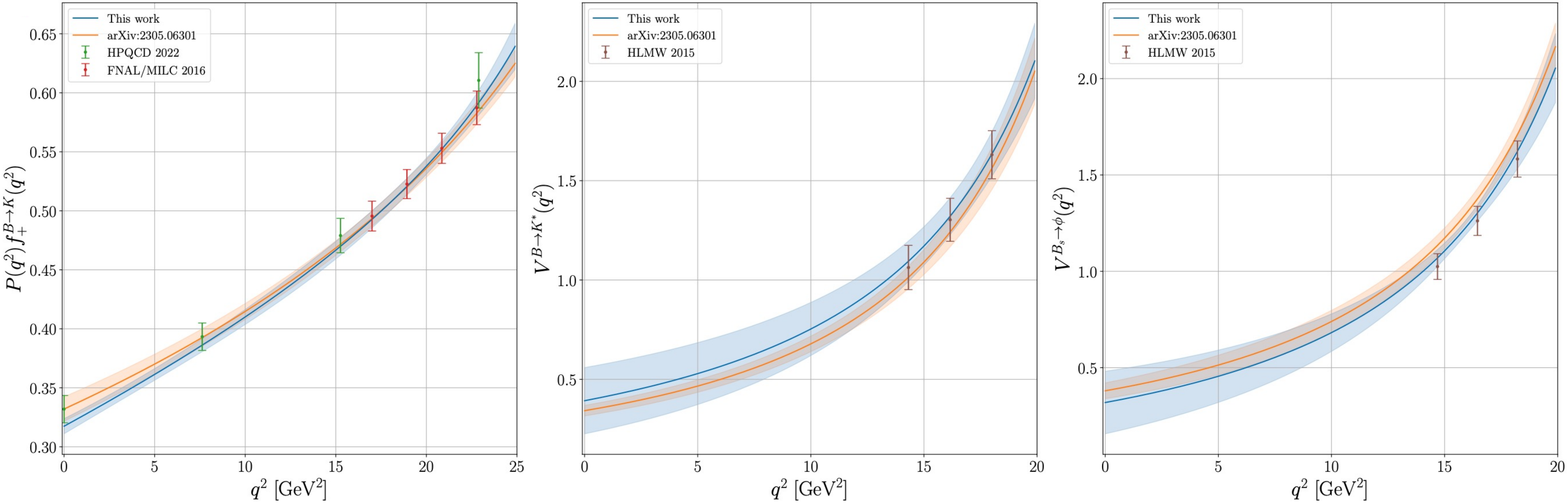

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Nice consistency w/ the results of
Gubernari et al, JHEP '23 [2305.06301]

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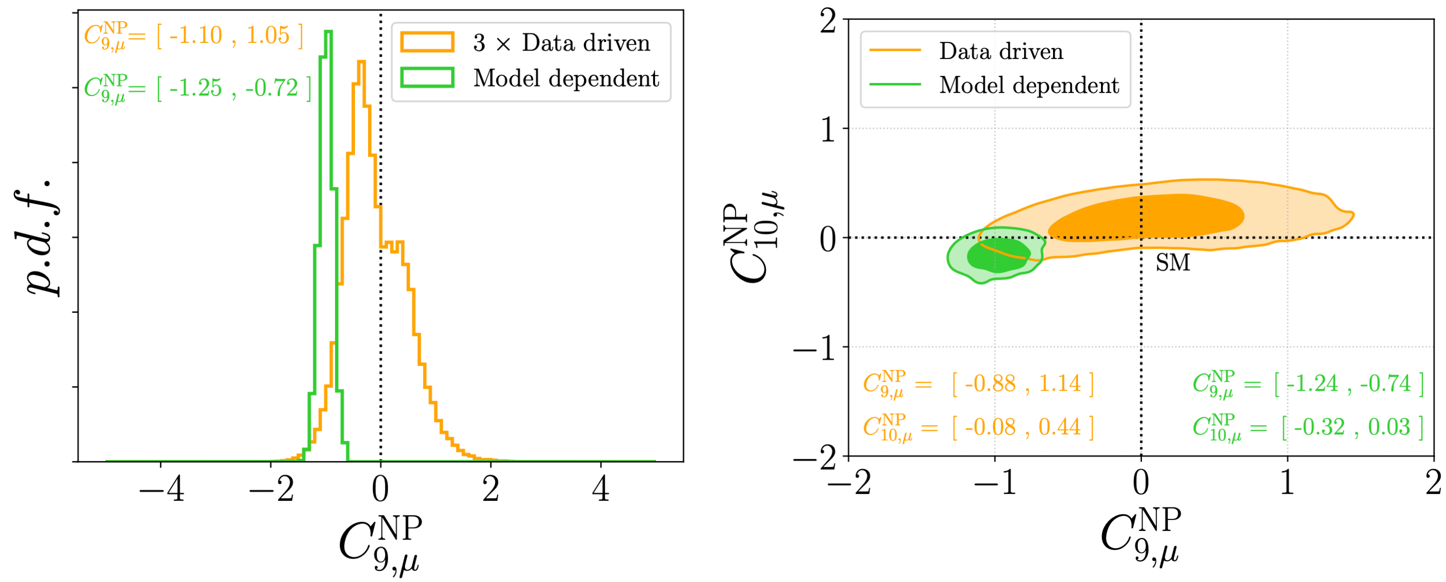
Which is their contribution ? No general consensus on the answer to this question:

M. Ciuchini et al, PRD 107 2023 5 [2212.10516]



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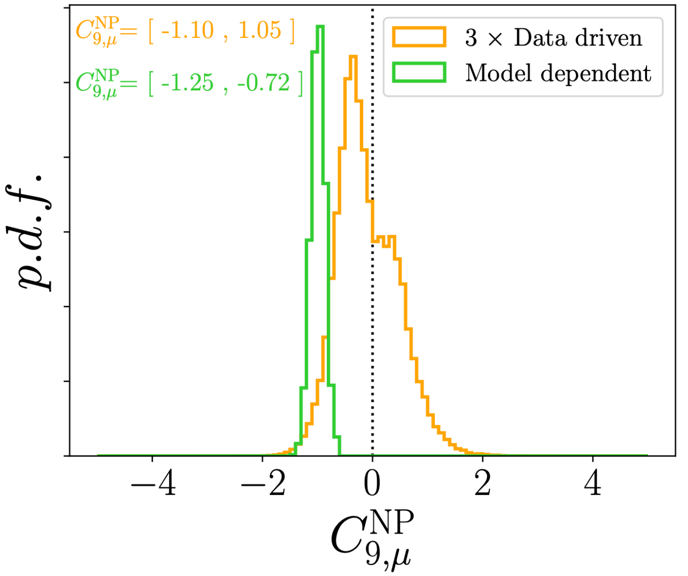

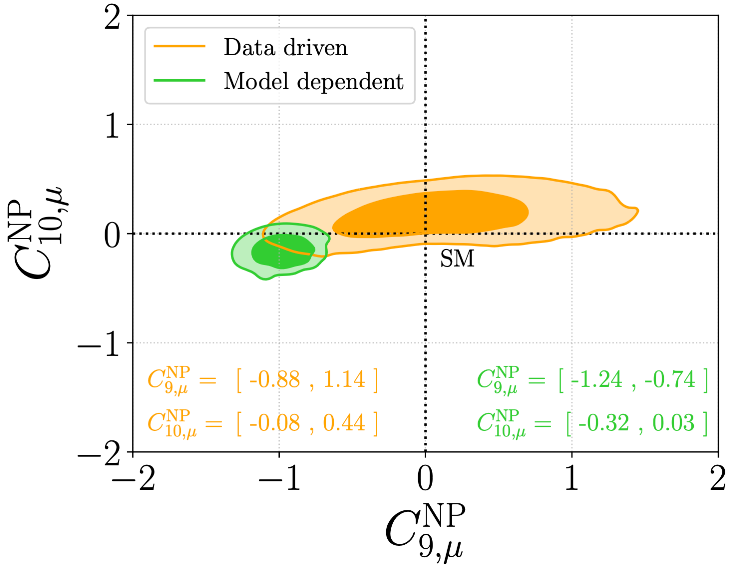

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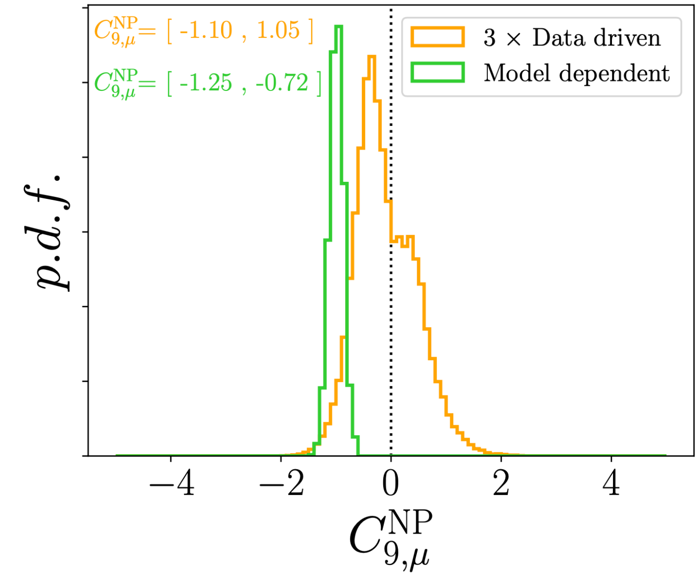

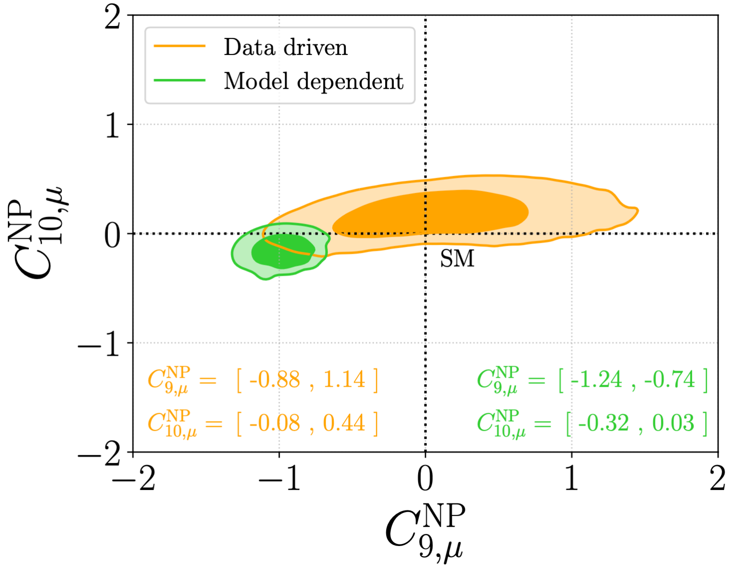

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Advantage: clear synergy between hadronic contributions and New Physics!

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]

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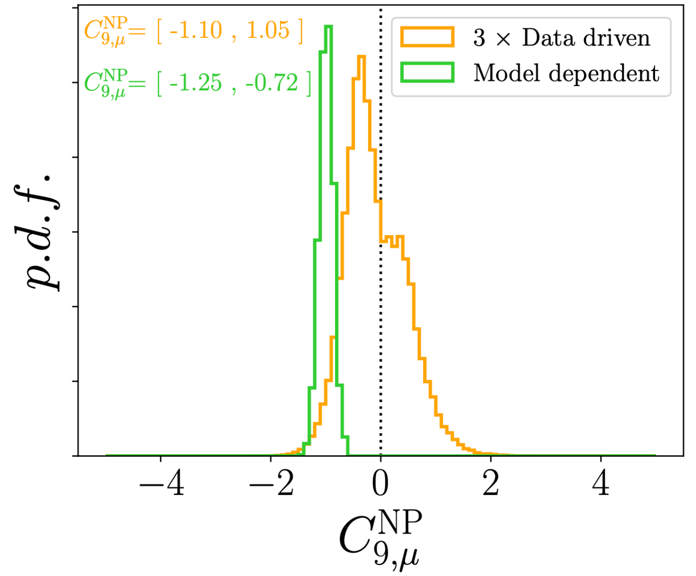

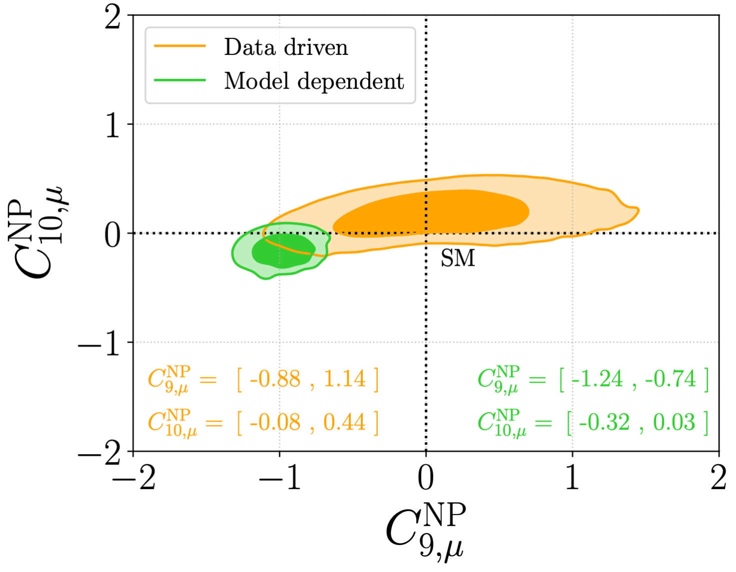

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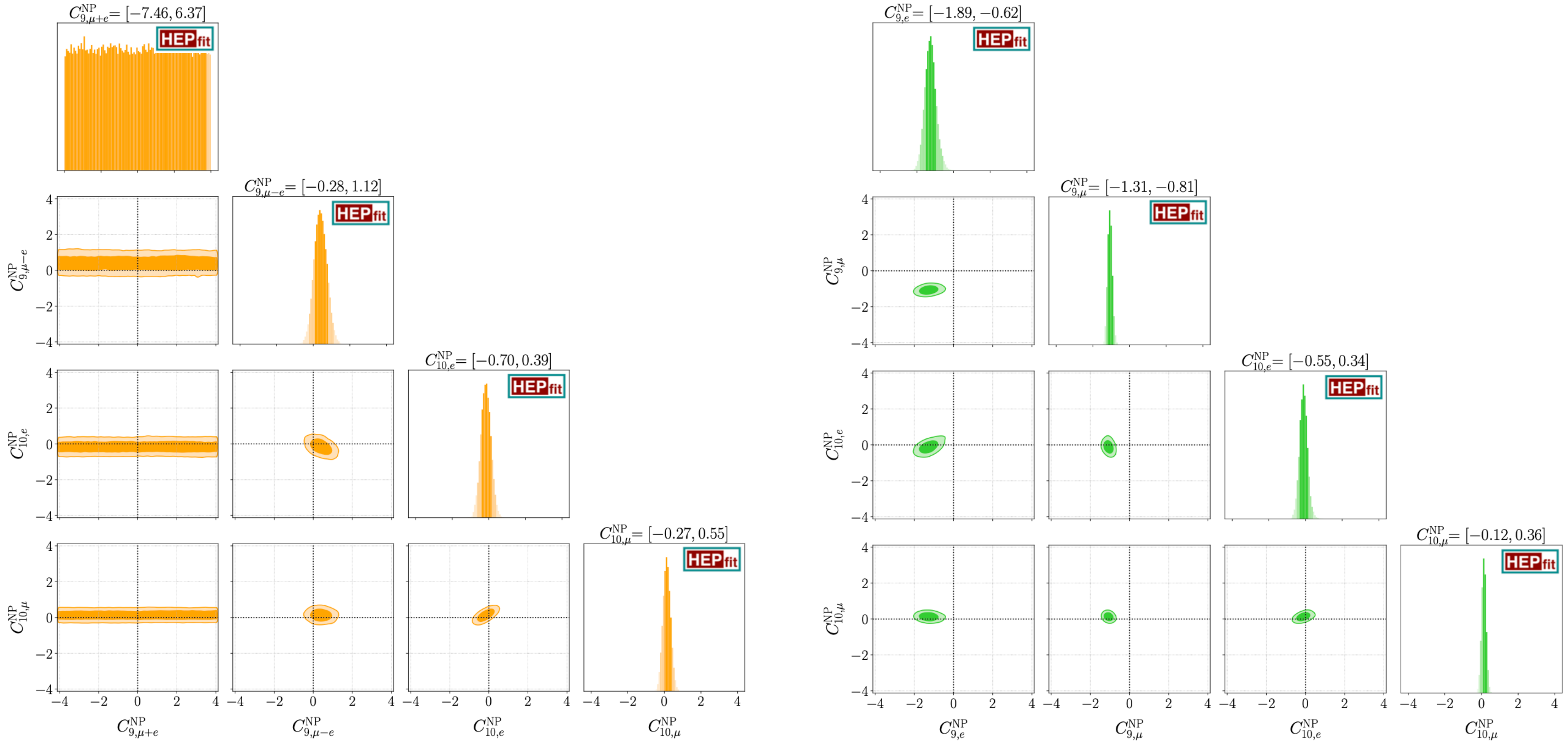
Model-depedent: the *h*-terms $[h_-^{(0)}, h_-^{(1)}, h_-^{(2)}]$ are considered *negligible*

Rationale: this assumption is supported by the results of the **application of dispersion relations, analiticity and unitarity (together with LCSR data used as inputs)!**

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

Non-local hadronic form factors

This conclusion is *__still true__* *for the 2025 update of* **Ciuchini et al., PRD 107 (2023) 5**:



M. Valli's talk @ 21st Rencontres du Vietnam: Flavour Physics Conference 2025

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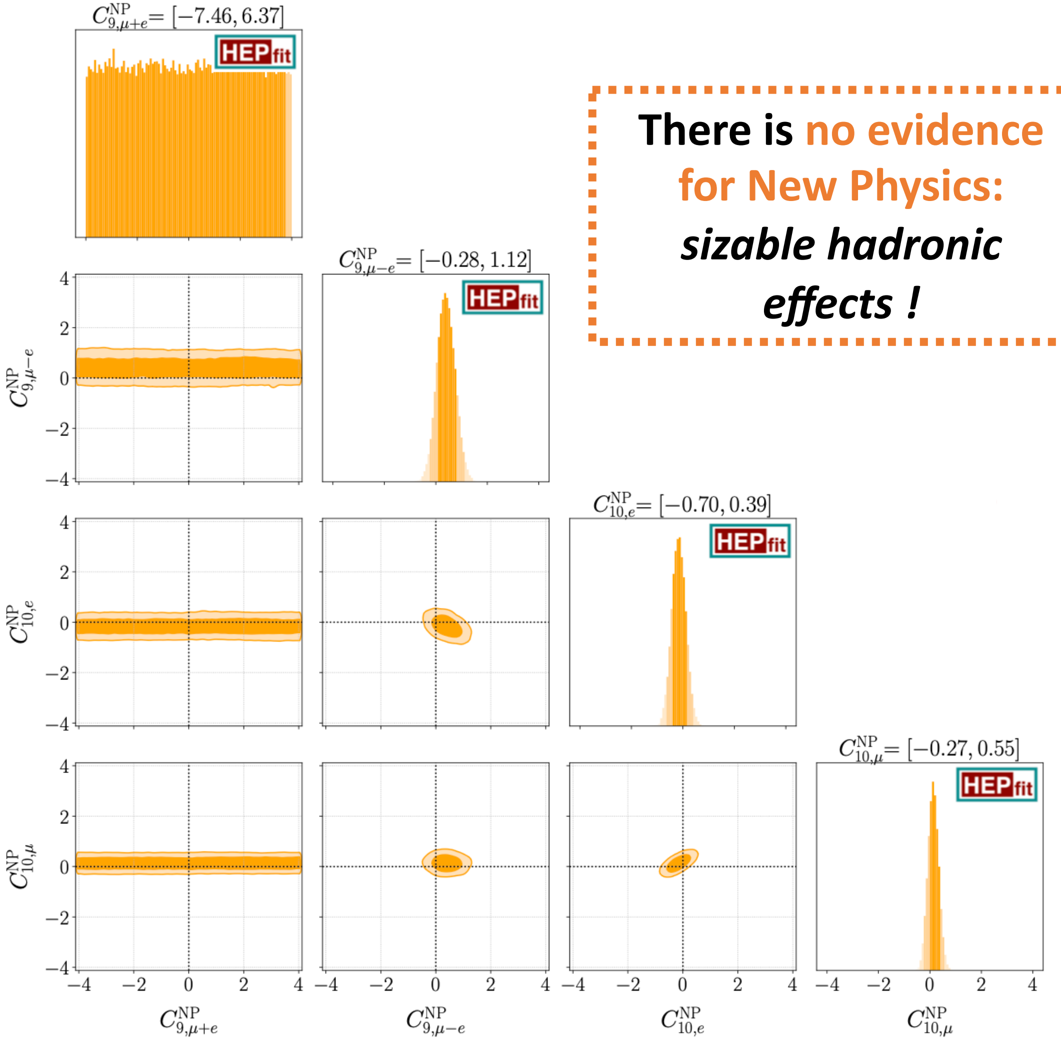
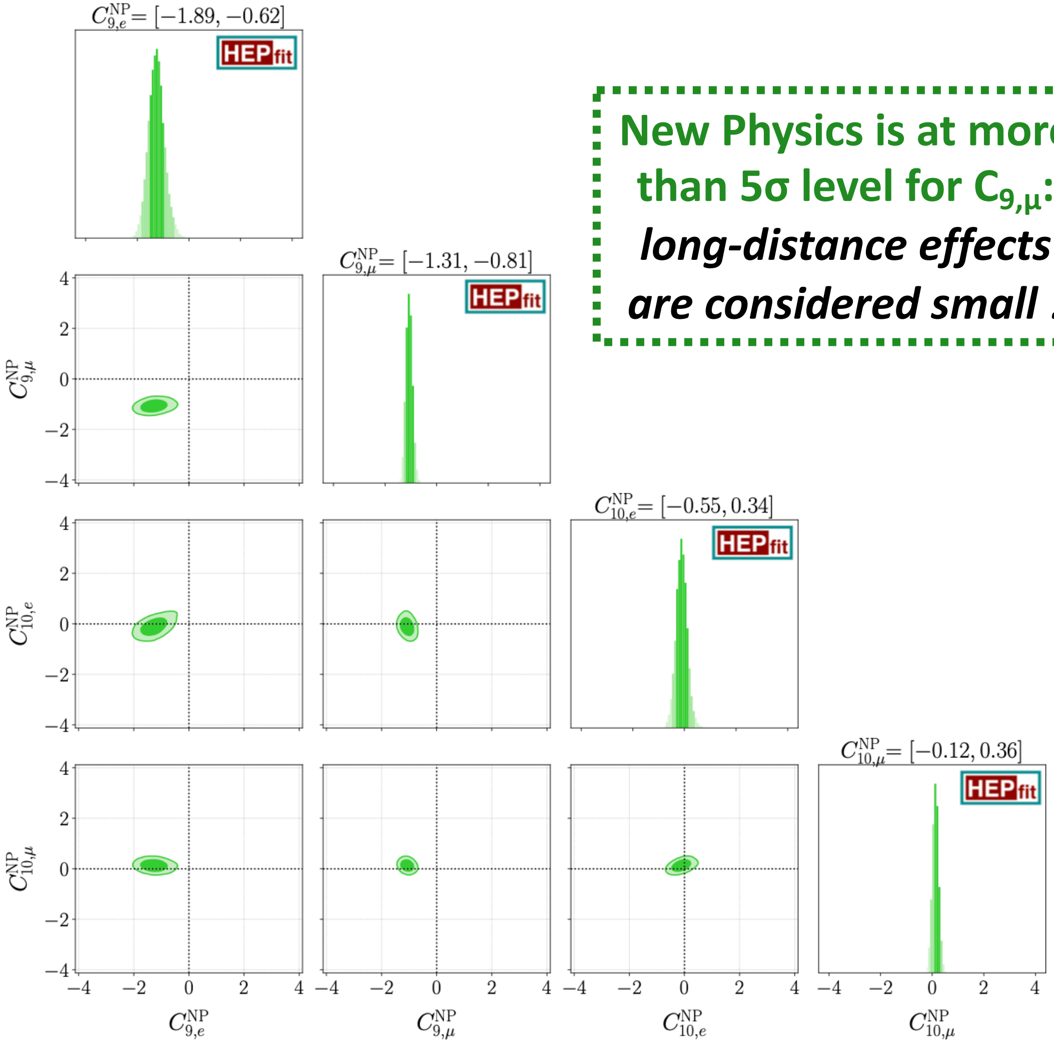


There is **no evidence for New Physics:**
sizable hadronic effects !



New Physics is at more than 5σ level for $C_{9,\mu}$:
long-distance effects are considered small !

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Possible directions for future work

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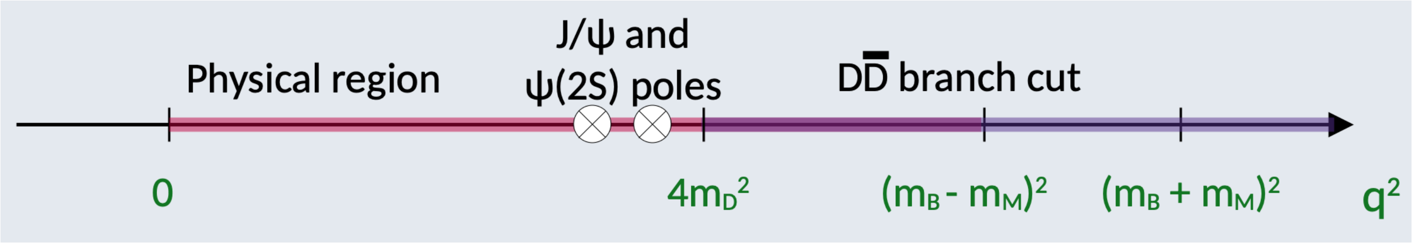

M. Reboud's talk @ Moriond EW 2025 Workshop

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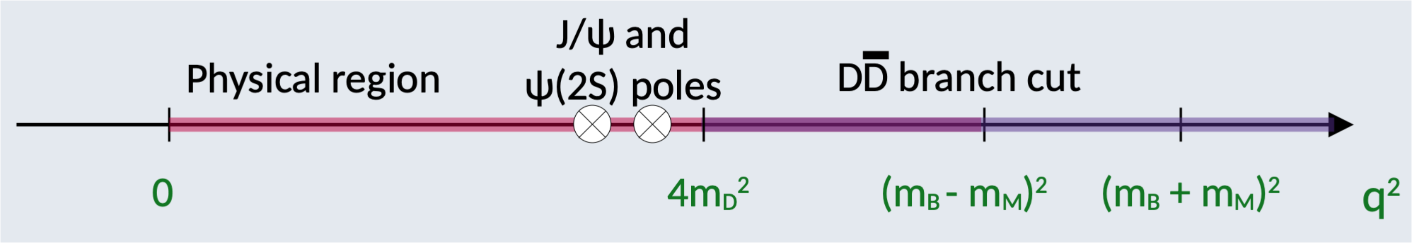
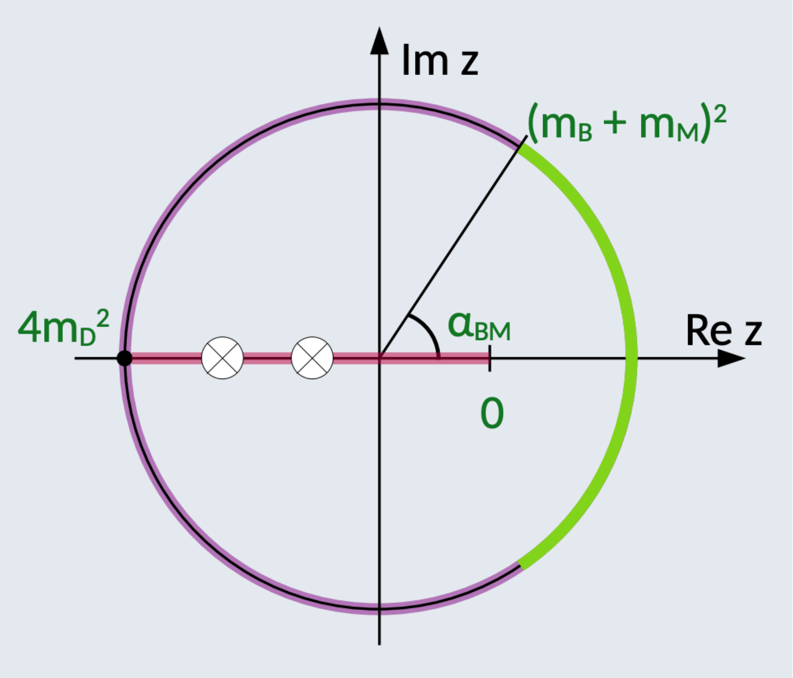


M. Reboud's talk @ Moriond EW 2025 Workshop

through an appropriate
conformal transformation $z = z(q^2)$



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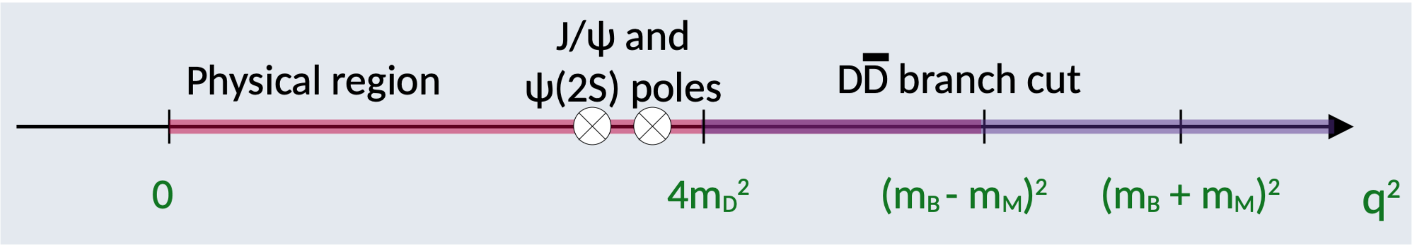

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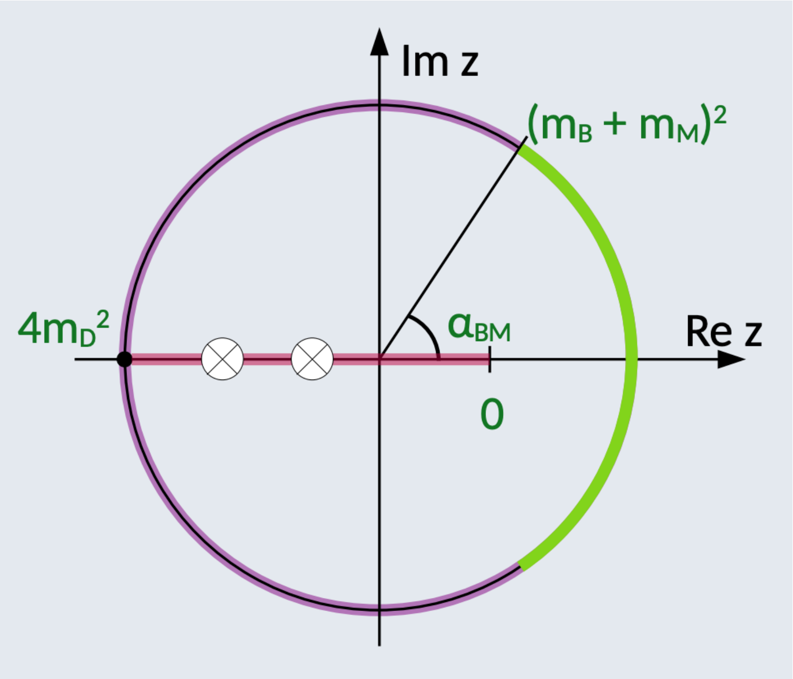

This conformal mapping allows to **expand the non-local FFs** on the green arc **using a set of orthonormal polynomials p_k** (see **Gubernari et al., 2011.09813, 2206.03797, 2305.06301**):

$$f(z) = \frac{\sqrt{\chi_+^U}}{\phi(z)B(z)} \sum_{k=0}^{\infty} c_k\, p_k(z;\alpha_{BM}) , \quad \sum_{k=0}^{\infty} c_k^2 \leq 1$$

(*Alternative expansion presented in* **Flynn et al, PRD '23 [2303.11280]**)

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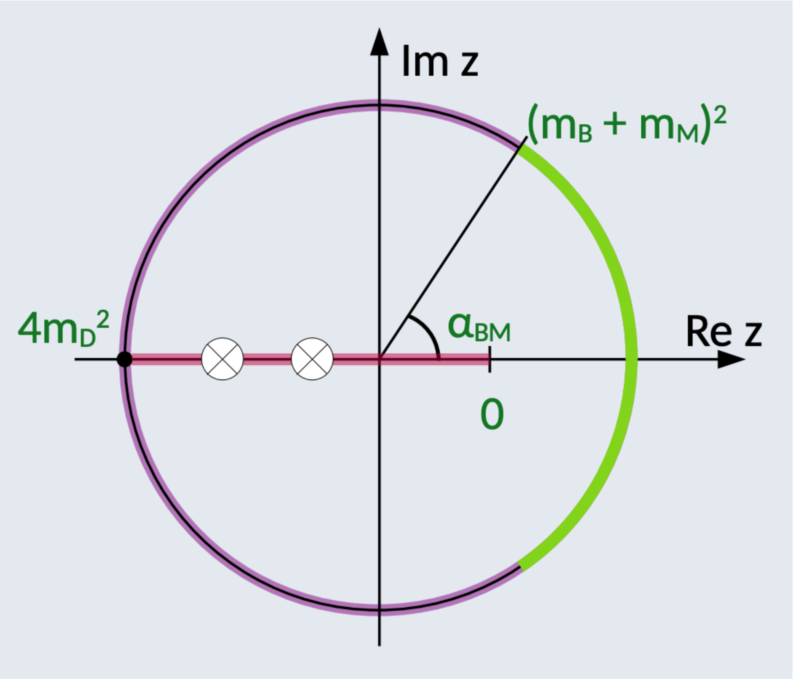
1. ***Further investigation of sub-threshold effects for non-local FFs:*** such FFs are indeed characterized by a branch-cut starting @ $q^2 = (2m_D)^2$

This parametrization has been also used in recent analyses by the LHCb Collaboration, see for instance the "Amplitude analysis of the $B \to K^* \mu^+ \mu^-$ decay" in ***PRL 132 (2024) 13 [2312.09115]***

This conformal mapping allows to **expand the non-local FFs** on the green arc **using a set of orthonormal polynomials p_k** (see **Gubernari et al., 2011.09813, 2206.03797, 2305.06301**):

$$f(z) = \frac{\sqrt{\chi_+^U}}{\phi(z) B(z)} \sum_{k=0}^{\infty} c_k \, p_k(z; \alpha_{BM}), \qquad \sum_{k=0}^{\infty} c_k^2 \leq 1$$



(*Alternative expansion presented in* **Flynn et al, PRD '23 [2303.11280]**)

Possible directions for future work

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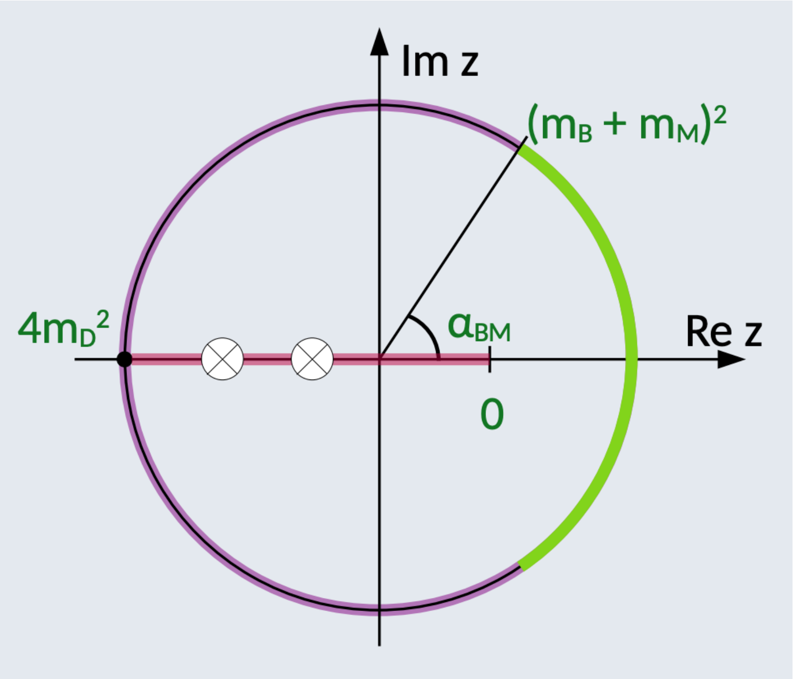

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$$\frac{1}{2\pi}\int_{-\alpha_{BM}}^{\alpha_{BM}} d\alpha \left|\phi(e^{i\alpha}) f(e^{i\alpha})\right|^2 \leq \chi_+^U ,$$

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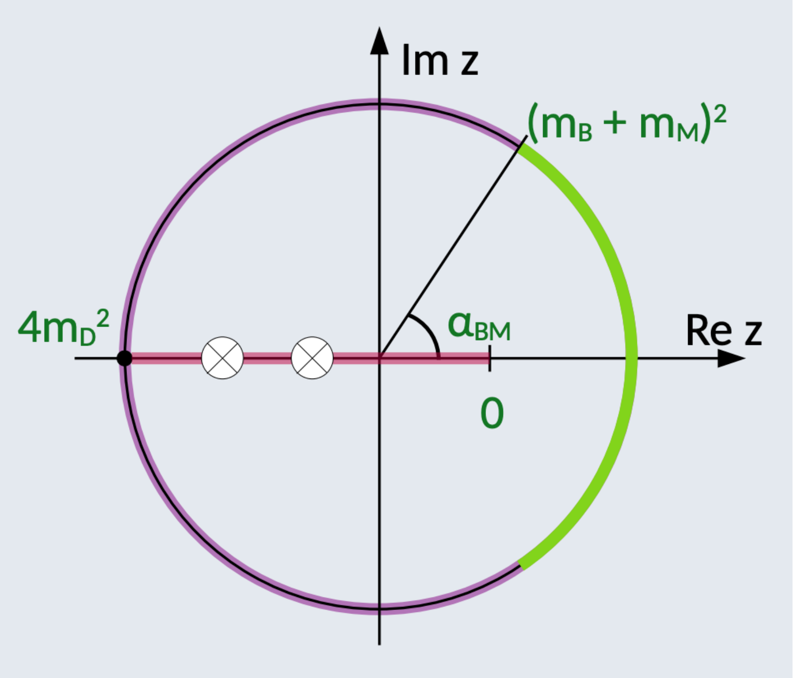

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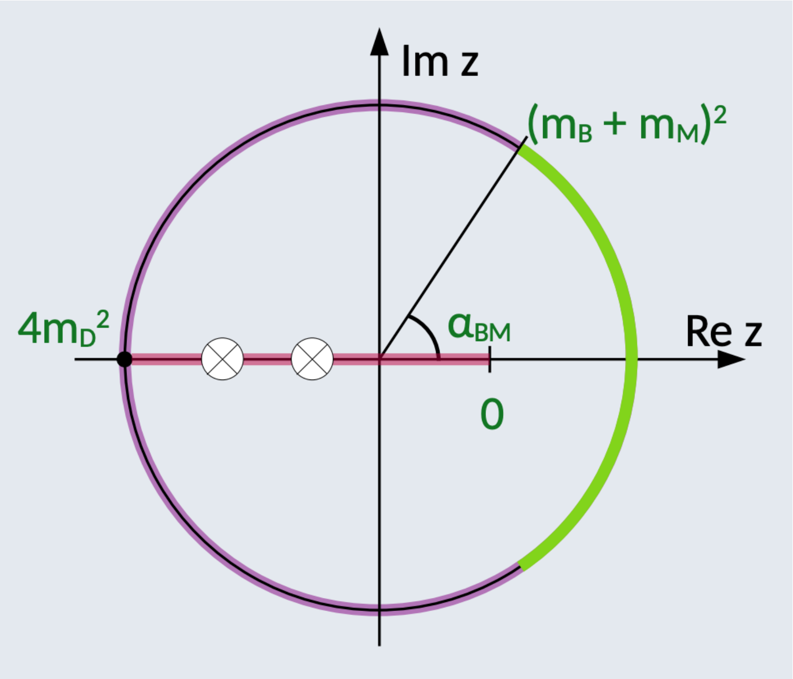

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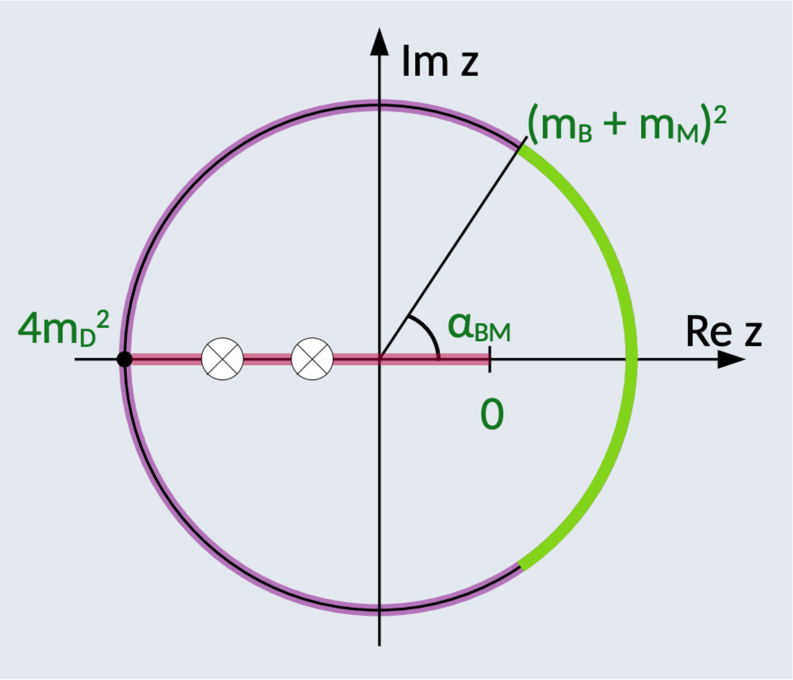

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This double dispersive bound may allow to corroborate previous findings concerning the application of unitarity and analiticity on non-local FFs !

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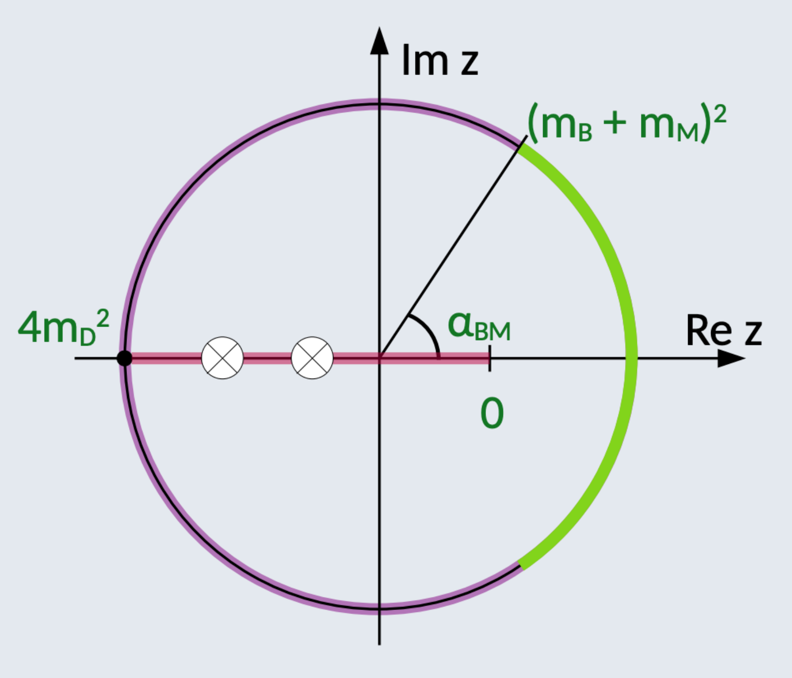

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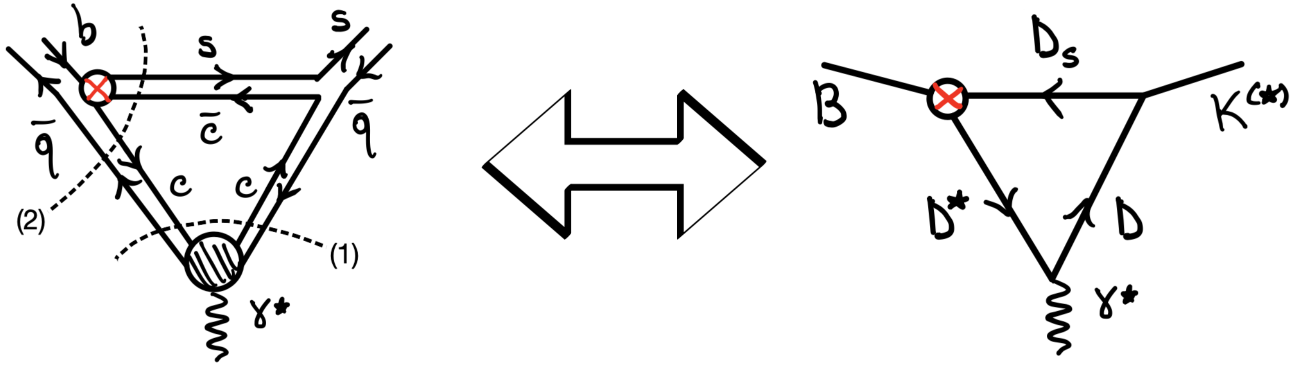

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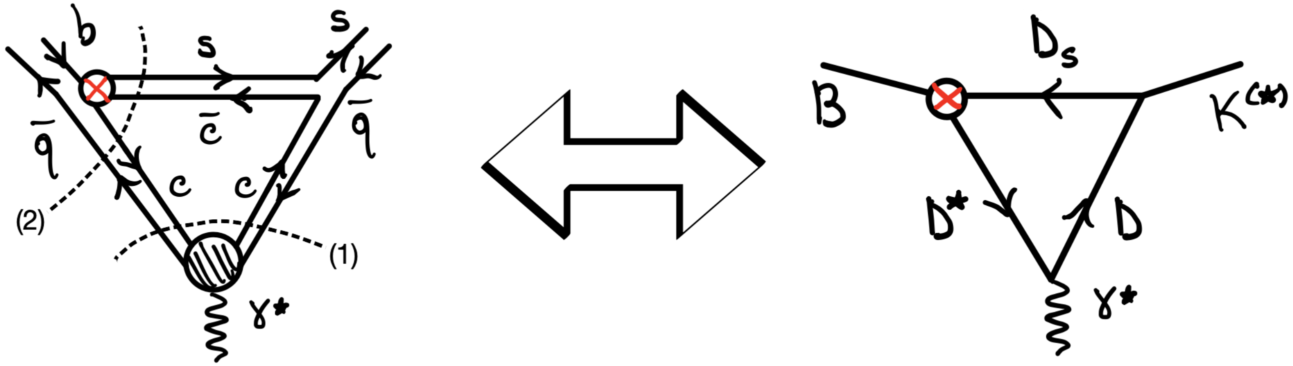

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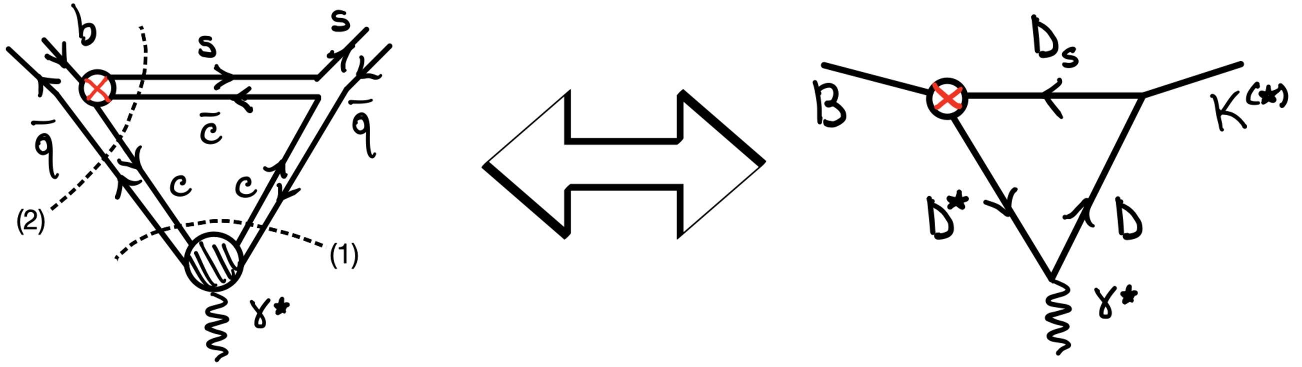

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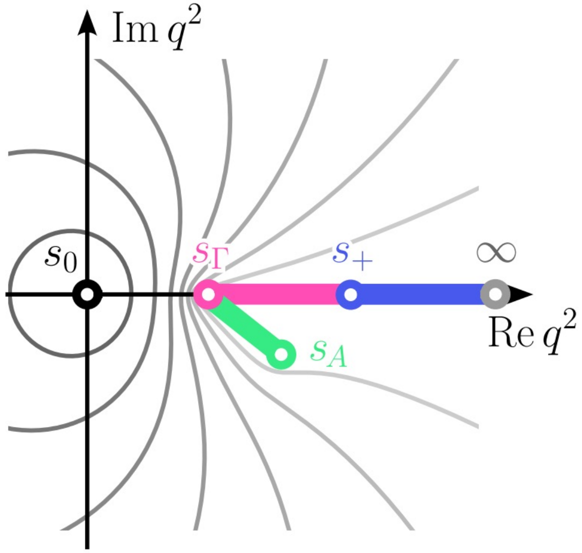

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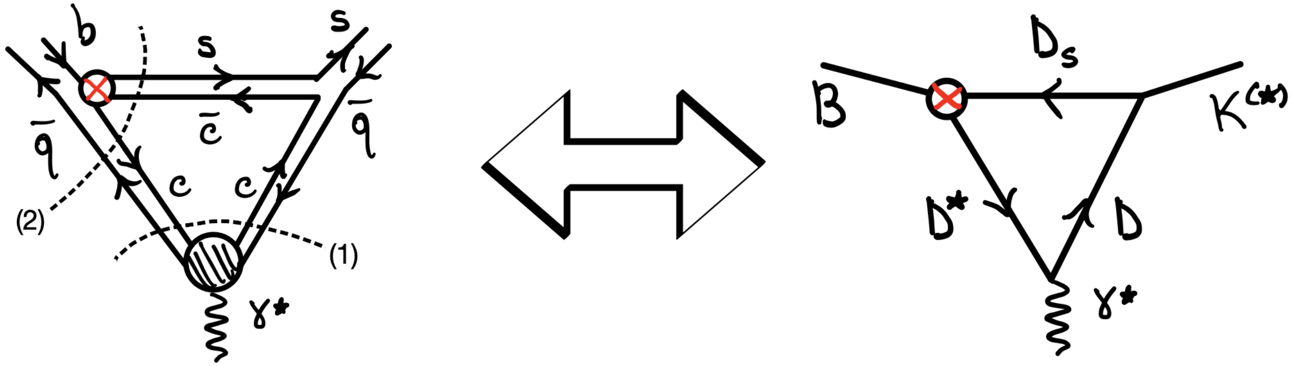

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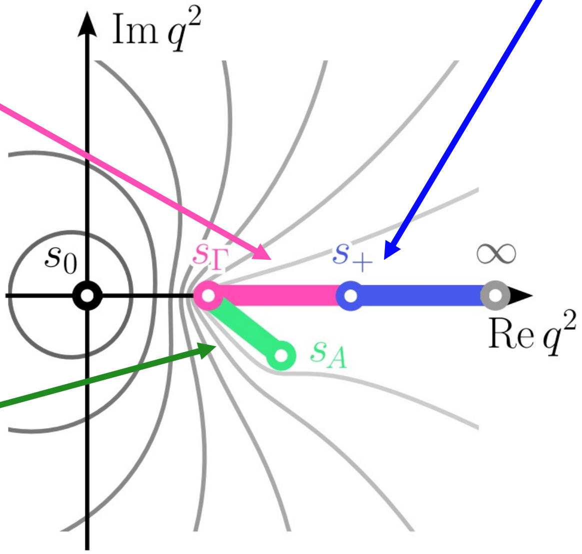

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taken from 2412.04388

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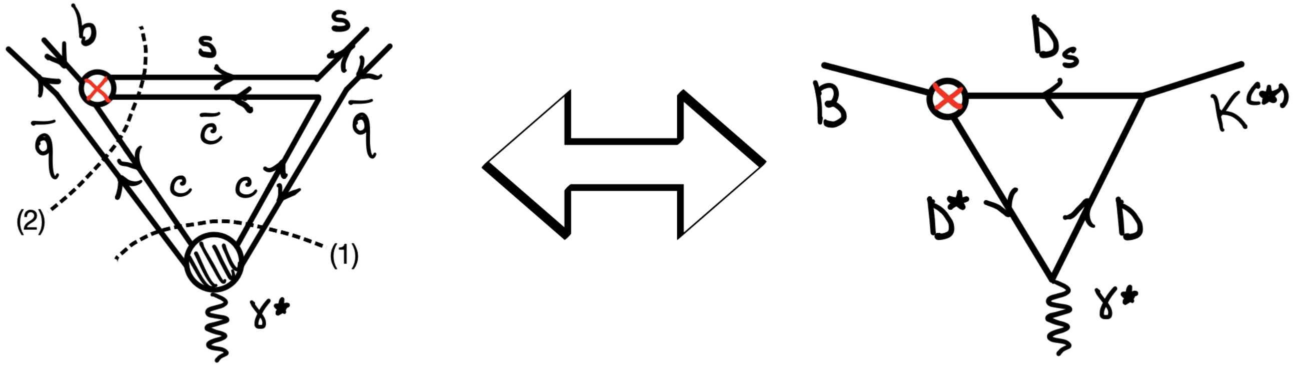

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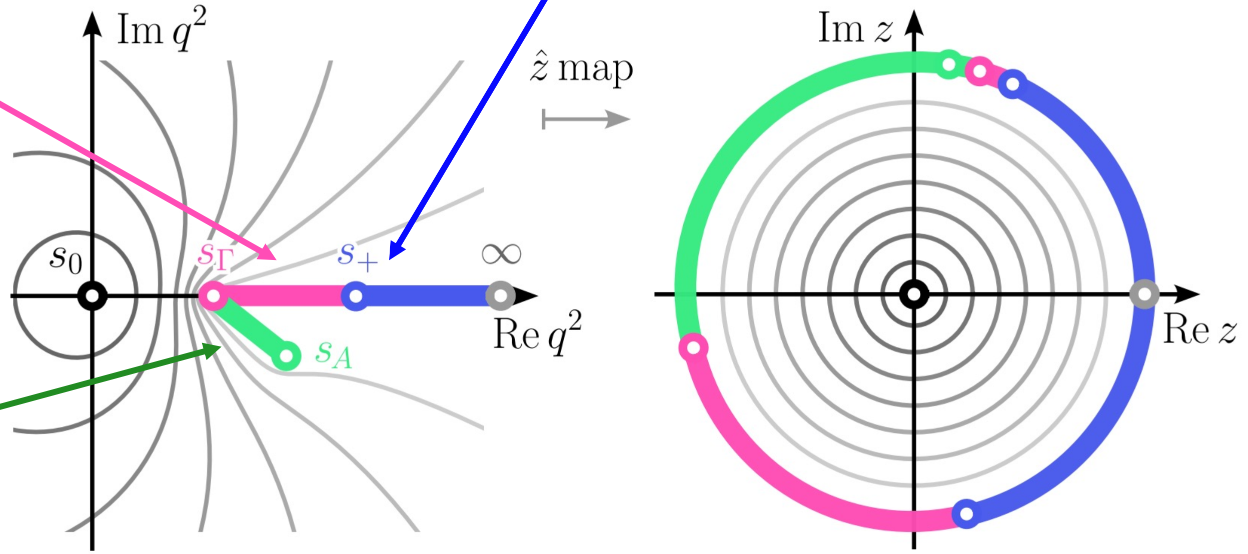

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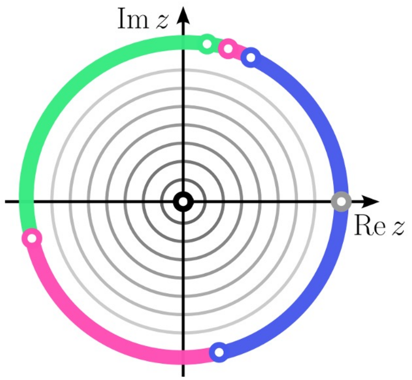
- A multiple dispersive bounds (i.e. an extension of what discussed for sub-thresholds) can be a proper way to implement unitarity here ?



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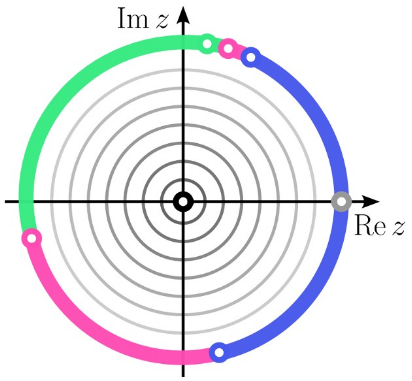

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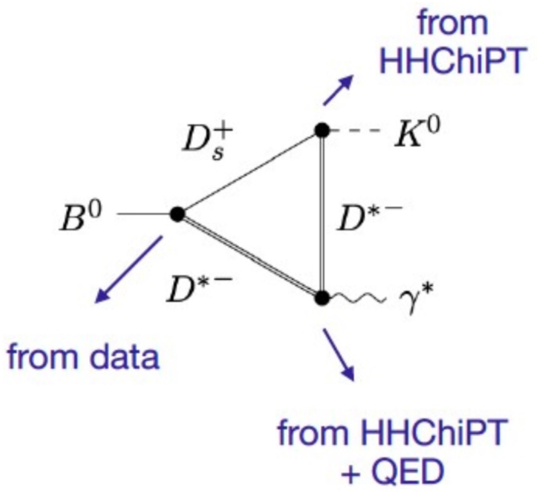
- Phenomenologial estimates can give us a complementary insight, see **Isidori et al., PRD '25 [2405.17551] and EPJC '25 [2507.17824]**



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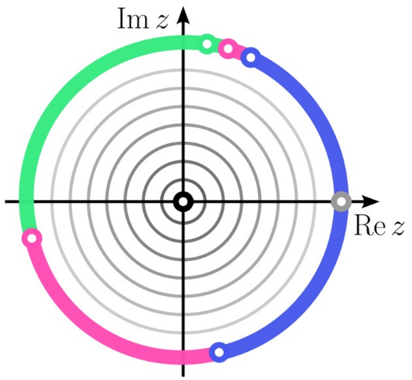

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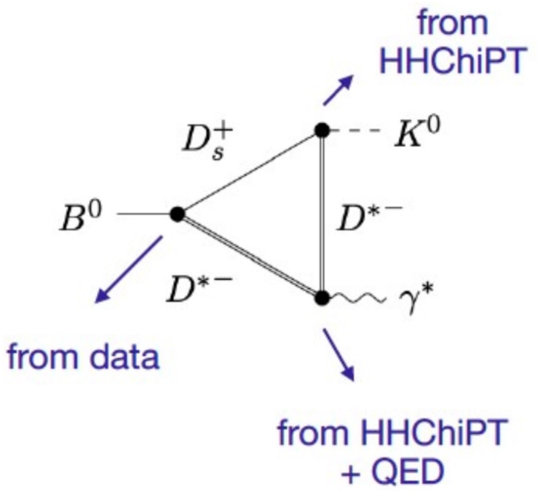

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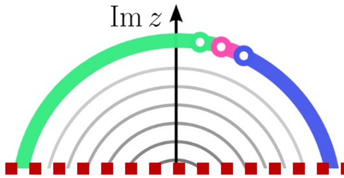

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Take-home message:

a lot of work still to be done !! ☺

This is, however, mandatory in order to confirm or not the presence of New Physics in semileptonic rare $B_{(s)}$ decays …

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Plan of the talk

a) Semileptonic neutral-current $B_{(s)}$-meson decays

b) Rare radiative-and-leptonic B_s-meson decay

c) Rare semileptonic decays with di-neutrino final states

Radiative-and-leptonic Bs decays

A novel possibility to analyze b → s quark transitions is the study of rare radiative-and-leptonic Bs decays. This is experimentally challenging, and the first world limit on this decay was set by LHCb (very close to the SM signal):

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) \; < \; 2.0 \times 10^{-9} \quad \left\{ m_{\mu\mu} > 4.9\,\mathrm{GeV}/c^2 \right\}$$

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

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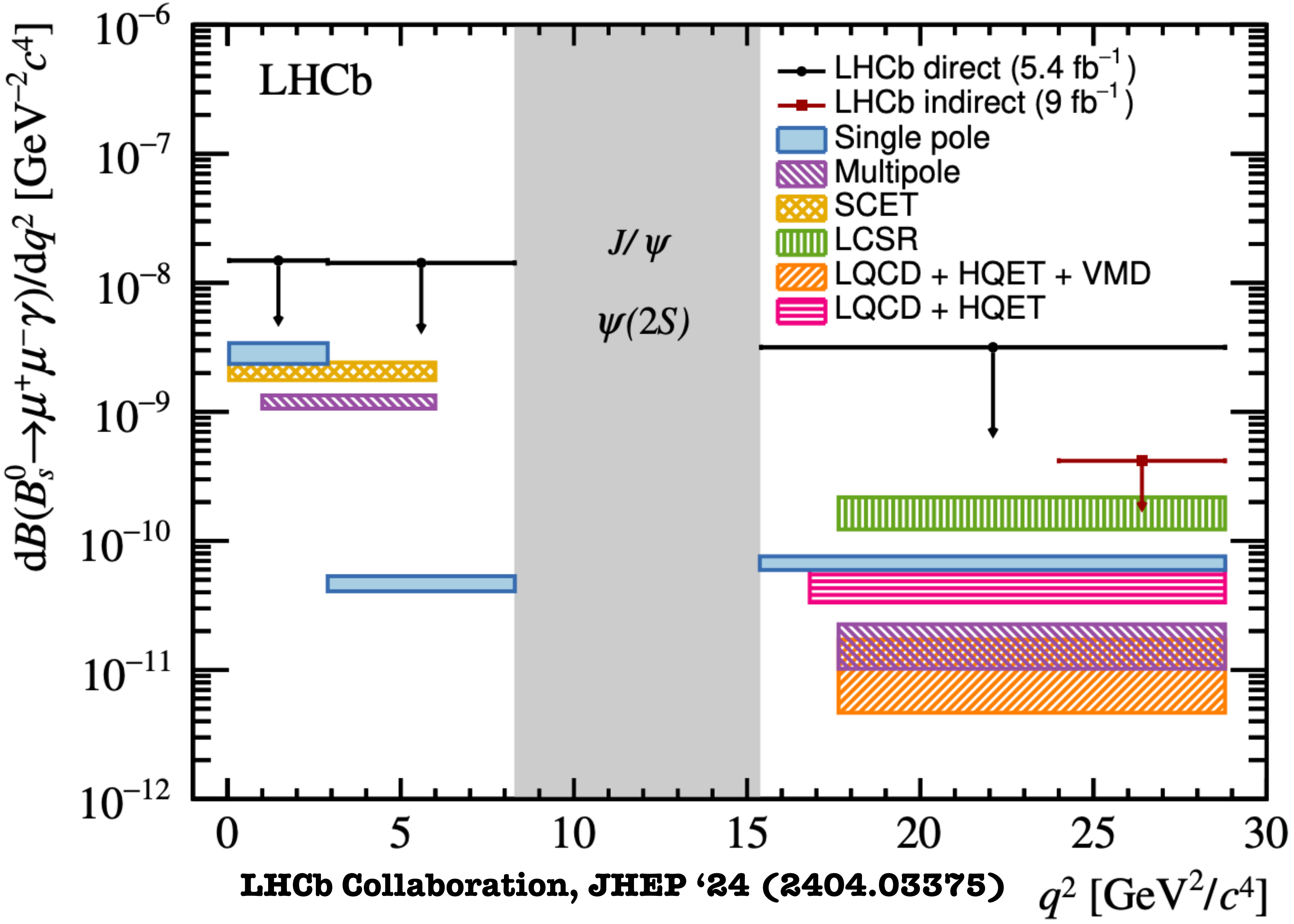
Several advantages from the phenomenological point of view:

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)** **[LHCb Coll., JHEP ‘24 (2404.03375)]**
- ***indirectly*** ***(i.e.*** **w/out photon reconstruction)** **[Dettori et al, PLB ’17 (1610.00629)]**

Summary of all (th. and exp.) results within the SM



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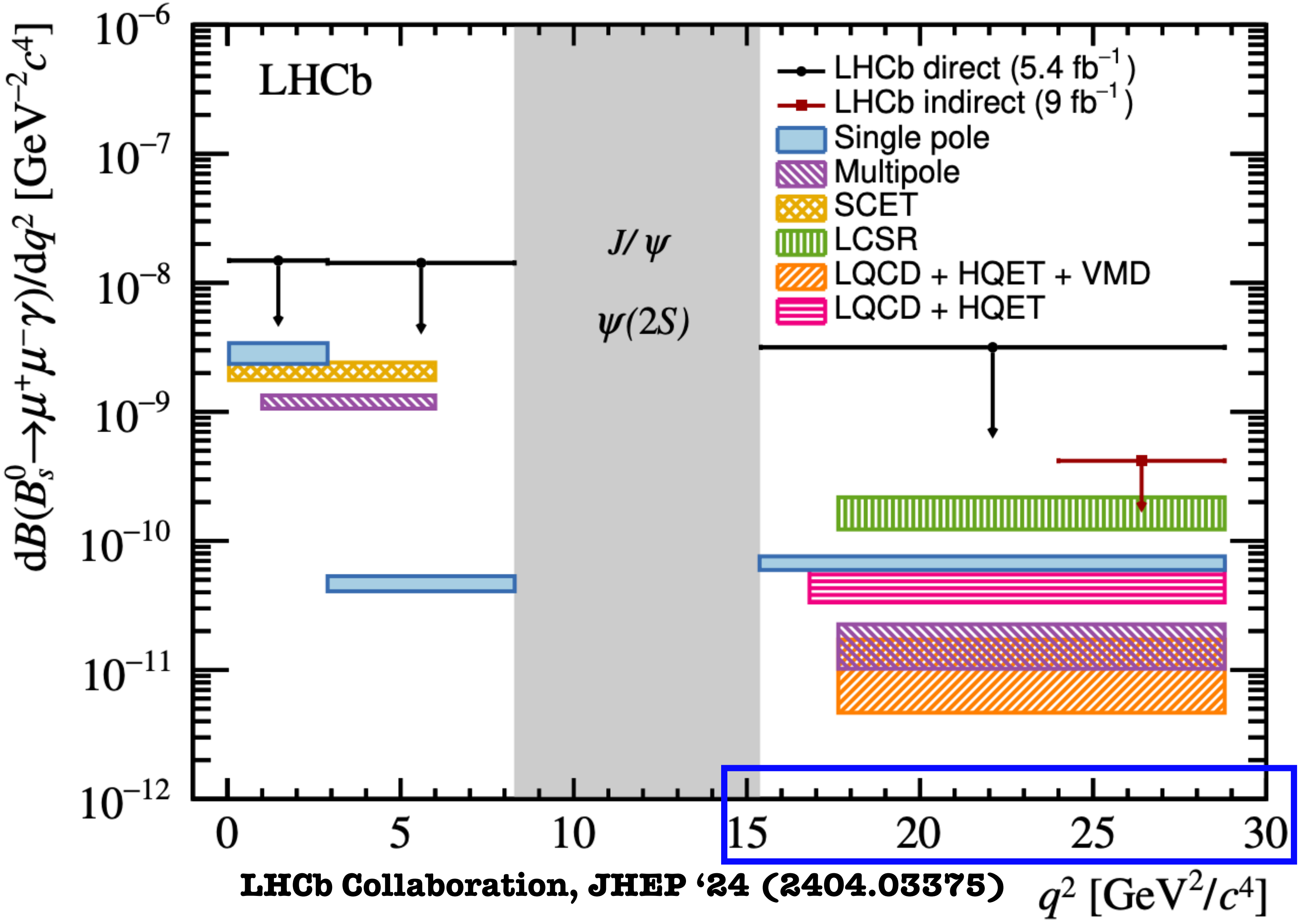

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As we will see in the next slide, the high-q^2 region can be particularly interesting for phenomenology

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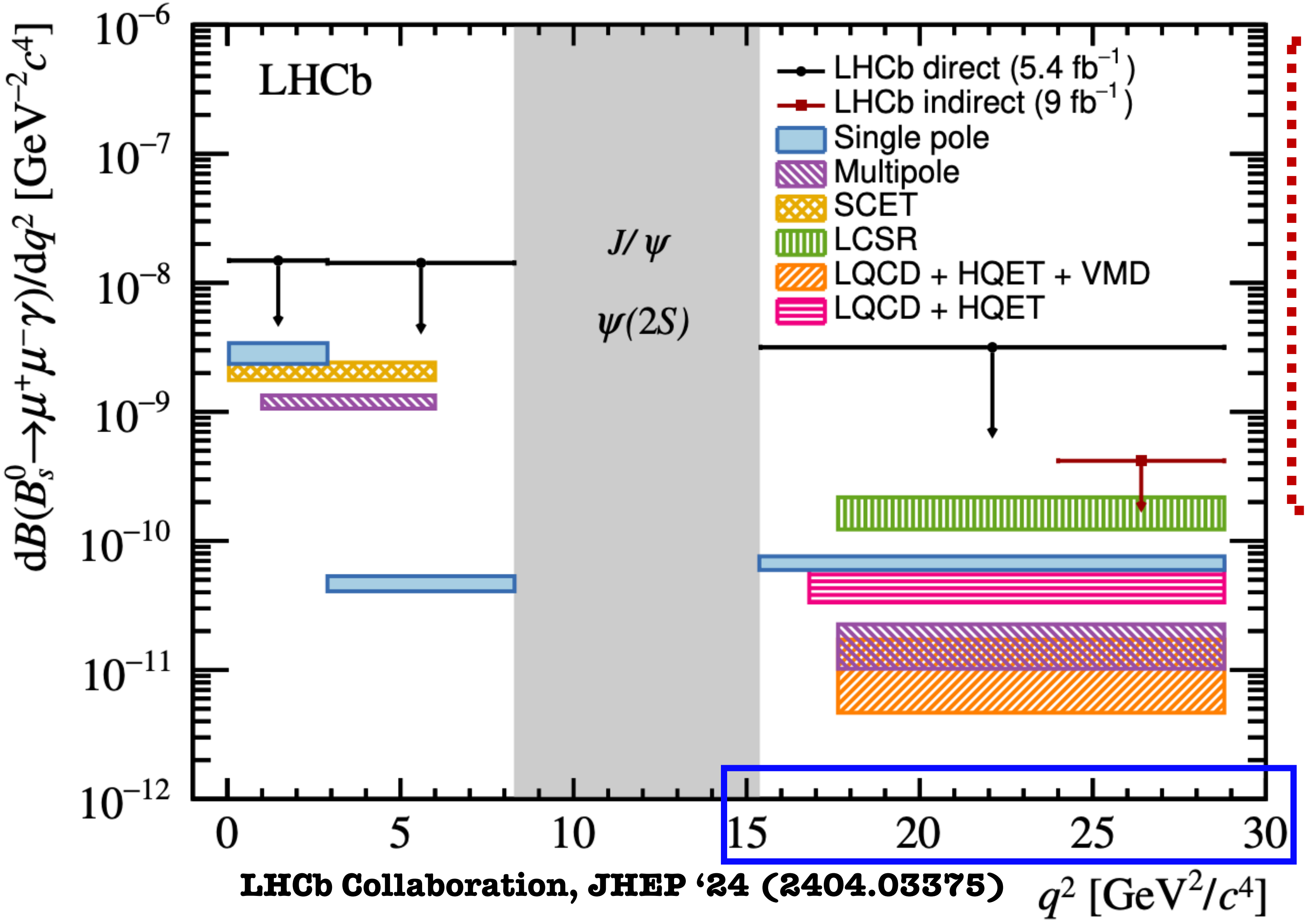

LHCb Collaboration, JHEP '24 (2404.03375)

In the next years, it is well reasonable to expect that a measurement will be finally available !

As we will see in the next slide, the high-q^2 region can be particularly interesting for phenomenology

$B_s \to \mu\mu\gamma$ at high-q2 in connection with semilept. B decays

<u>KEY IDEA:</u> BR($B_s \to \mu\mu\gamma$) @ high-q2 is 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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KEY IDEA: **BR($B_s \to \mu\mu\gamma$) @ high-q2 is sensitive to the very same short-distance physics present in B \to K(*) decays,** **without being affected by the same long-distance effects !**

Hence: **if there is really a NP contribution to C_9, this effect should influence as well the BR($B_s \to \mu\mu\gamma$) @ high-q2**

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Hence: **if there is really a NP contribution to C_9, this effect should influence as well the BR($B_s \to \mu\mu\gamma$) @ high-q2**

However, we do not have a direct measurement of BR($B_s \to \mu\mu\gamma$) @ high-q2 at present …

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

$B_s \to \mu\mu\gamma$ at high-q2 in connection with semilept. B decays

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

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

$$\tilde{B}_1\left(\hat{s},\,\hat{t}\right) = 8\left[\hat{s}\,F_V(q^2)\,F_A(q^2)\,Re\left(C_{9V}^{eff\,*}(\mu,q^2)\,C_{10A}(\mu)\right)\right.$$
$$\left.+\,\hat{m}_b\,F_V(q^2)\,Re\left(C_{7\gamma}^*(\mu)\,\bar{F}_{TA}^*(q^2)\,C_{10A}(\mu)\right)+\hat{m}_b\,F_A(q^2)\,Re\left(C_{7\gamma}^*(\mu)\,\bar{F}_{TV}^*(q^2)\,C_{10A}(\mu)\right)\right],$$

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

$$F_1\left(\hat{s}\right) = \left(\left|C_{9V}^{\rm eff}(\mu,q^2)\right|^2\,+\,\left|C_{10A}(\mu)\right|^2\right)F_V^2(q^2)\,+\,\left(\frac{2\hat{m}_b}{\hat{s}}\right)^2\left|C_{7\gamma}(\mu)\,\bar{F}_{TV}(q^2)\right|^2$$
$$+\,\frac{4\hat{m}_b}{\hat{s}}\,F_V(q^2)\,Re\left(C_{7\gamma}(\mu)\,\bar{F}_{TV}(q^2)\,C_{9V}^{eff\,*}(\mu,q^2)\right),$$

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

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

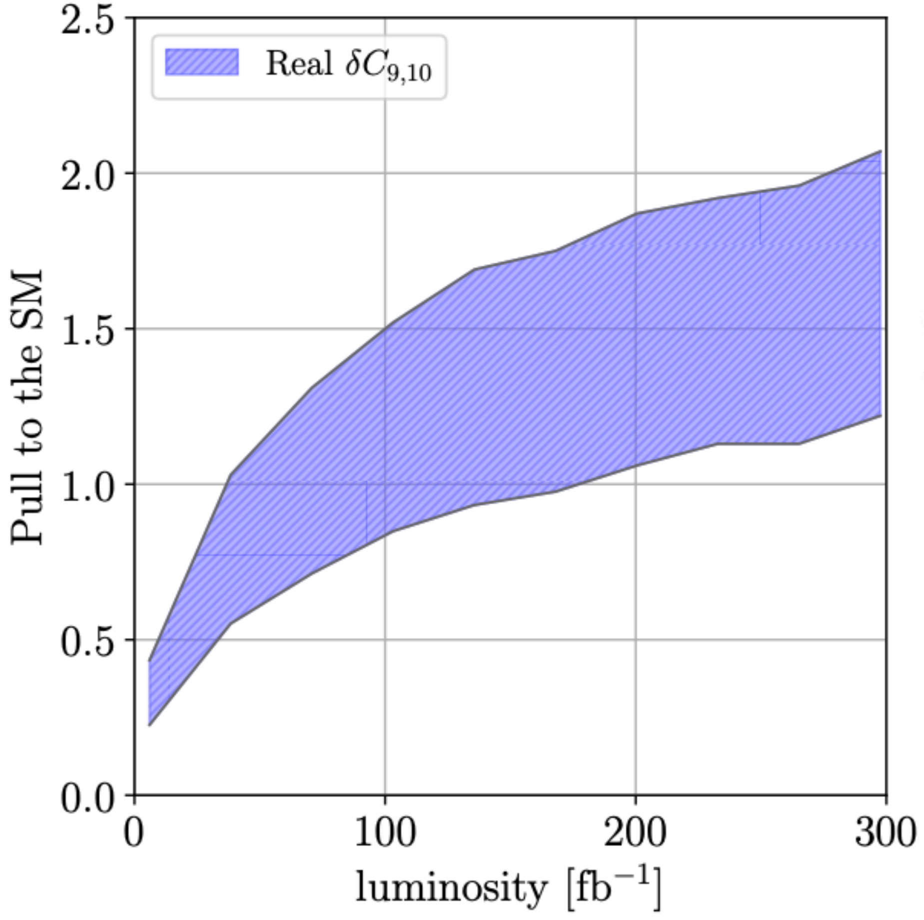
Bremsstrahlung

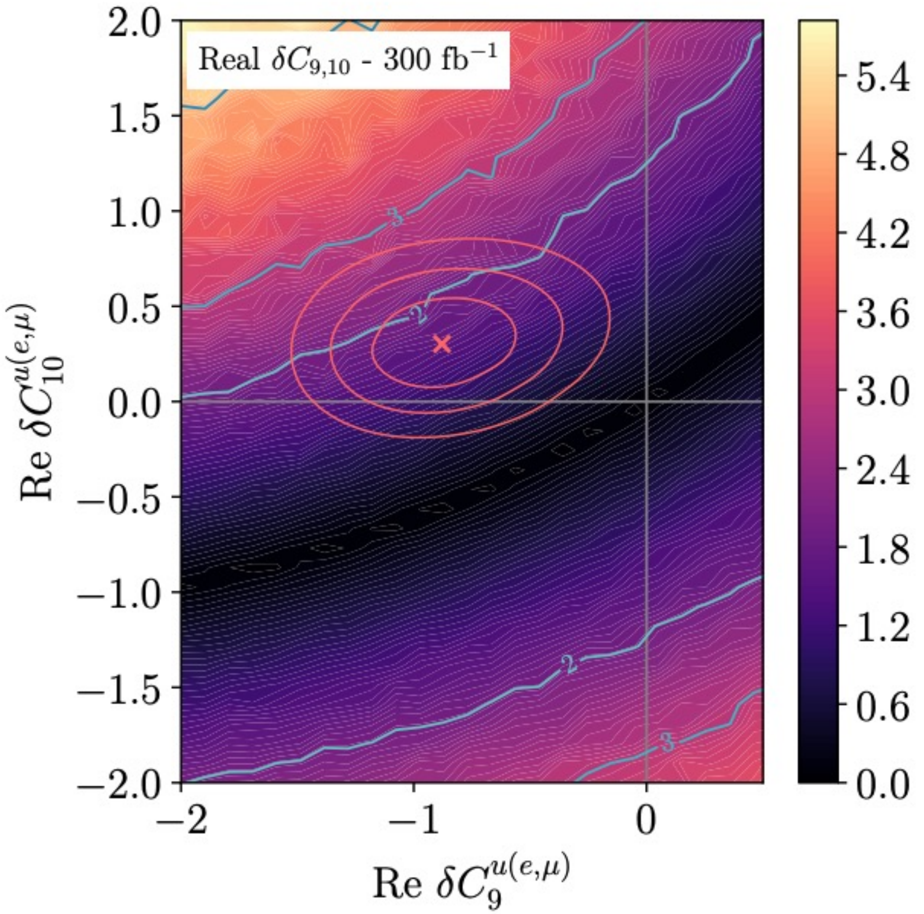
$$\boxed{\frac{d^2\Gamma^{(12)}}{d\hat{s}\,d\hat{t}}} = -\frac{G_F^2\,\alpha_{em}^3\,M_1^5}{2^{10}\,\pi^4}\,\left|V_{tb}\,V_{tq}^*\right|^2\,\frac{16\,f_{B_q}}{M_B}\,\hat{m}_l^2\,\frac{x^2}{(\hat{u}\,-\,\hat{m}_l^2)(\hat{t}\,-\,\hat{m}_{l34}^2)} \tag{6.3}$$
$$\times\left[\frac{2\,x\,\hat{m}_b}{\hat{s}}\,Re\left(C_{10A}^*(\mu)C_{7\gamma}(\mu)\bar{F}_{TV}(q^2,0)\right)\,+\,x\,F_V(q^2)\,Re\left(C_{10A}^*(\mu)C_{9V}^{\rm eff}(\mu,q^2)\right)+\,\xi(\hat{s},\hat{t})\,F_A(q^2)\,\left|C_{10A}(\mu)\right|^2\right].$$

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

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

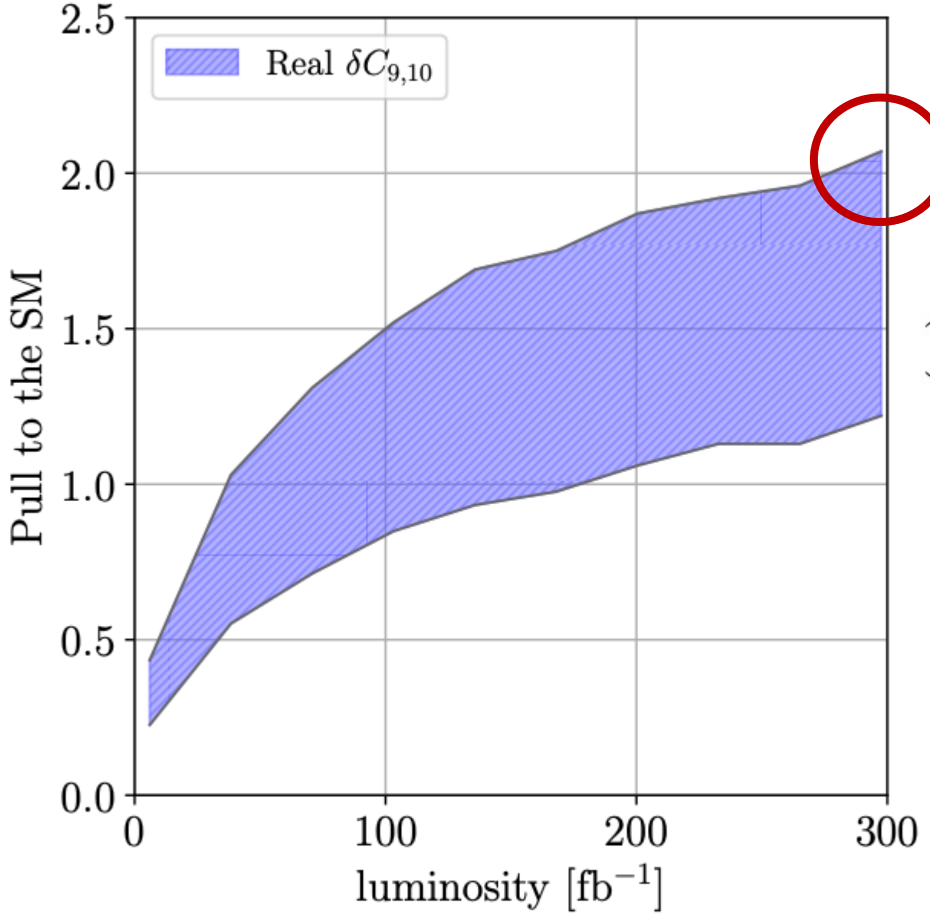


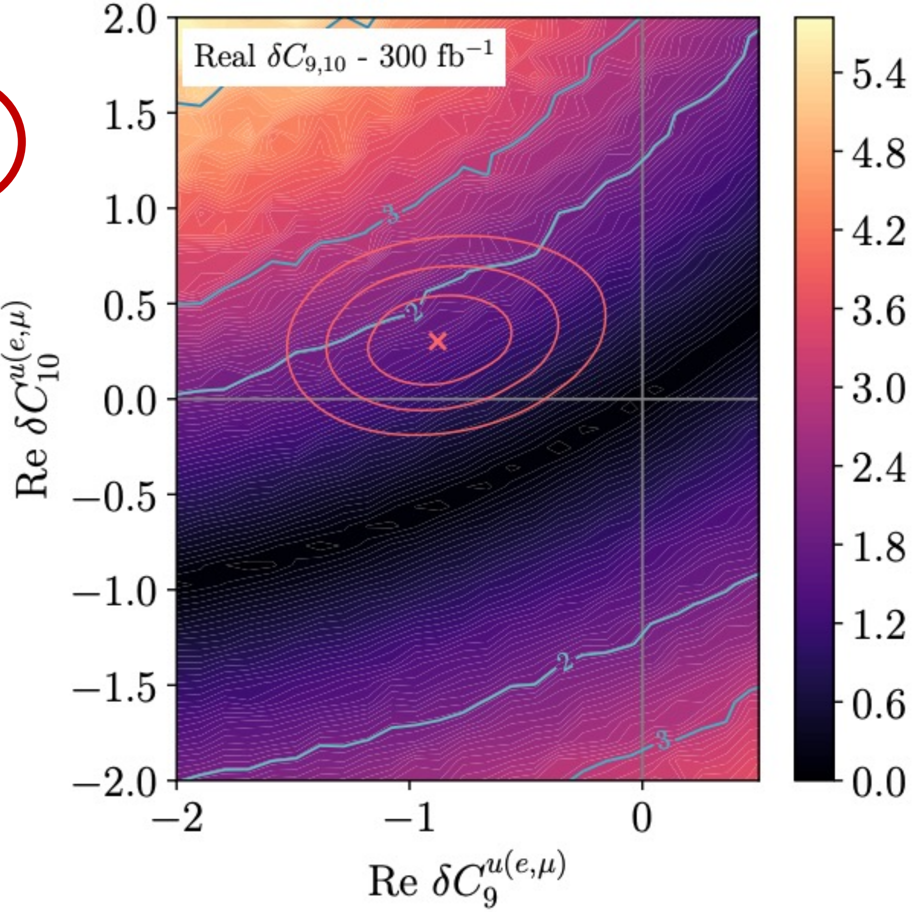


Pull to the SM of the BR **assuming NP in both C_9, C_{10}**

Guadagnoli et al., JHEP '23 [2308.00034]

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





It reaches the 2σ level at the border of the 1σ region for the WC shift!

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

Guadagnoli et al., JHEP '23 [2308.00034]

Plan of the talk

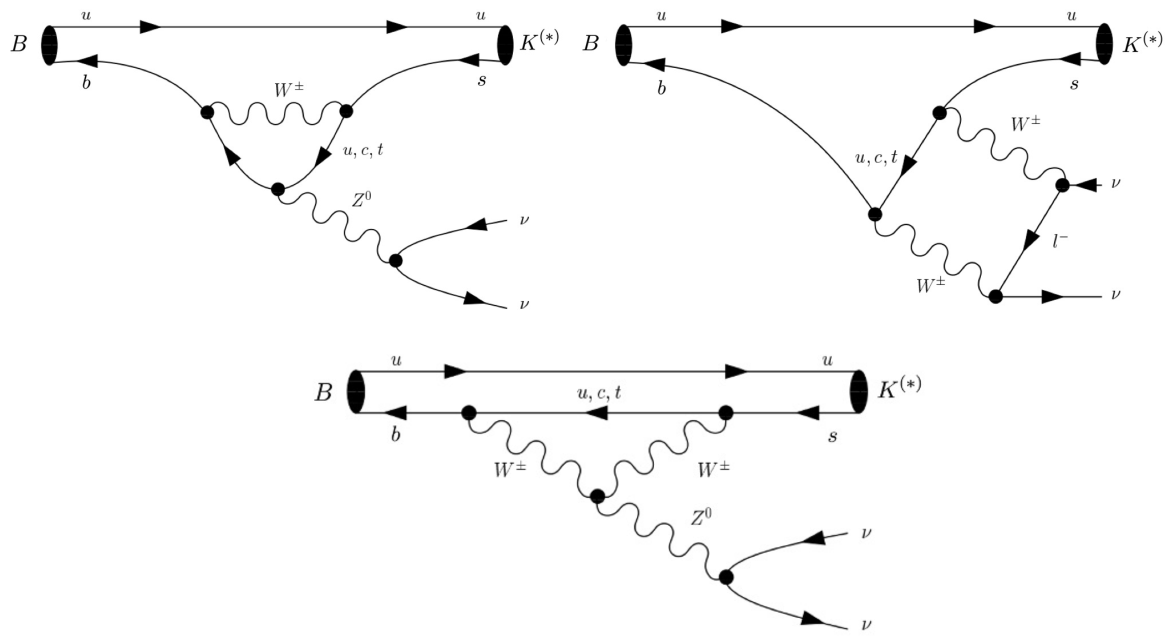
a) Semileptonic neutral-current $B_{(s)}$-meson decays

b) Rare radiative-and-leptonic B_s-meson decay

c) Rare semileptonic decays with di-neutrino final states

B → K(*)$\nu\nu$ decays

Long-distance effects here are much smaller than in B → K(*)ℓ+ℓ-



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Major sources of uncertainty:

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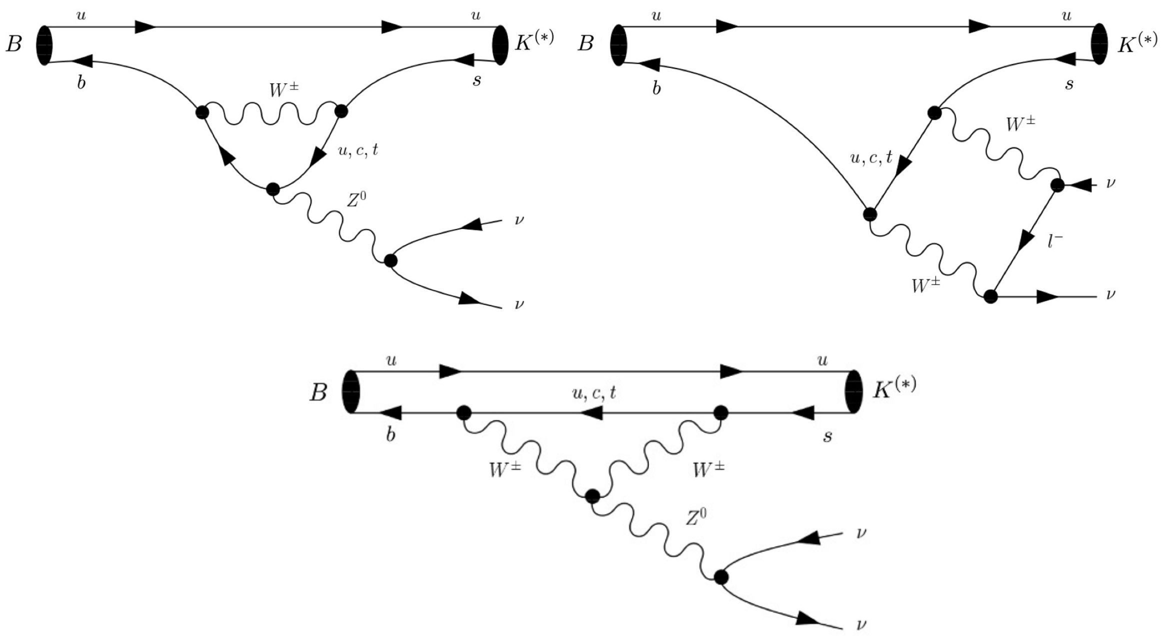

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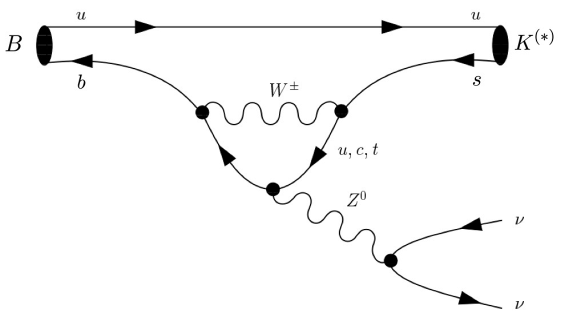
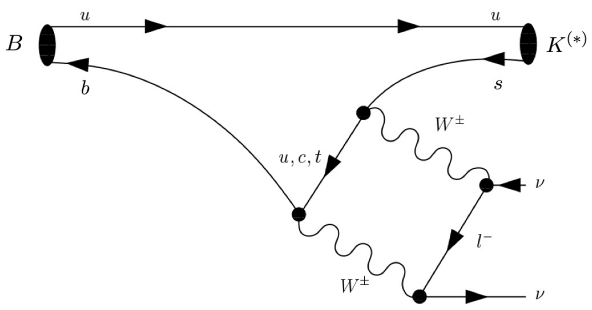
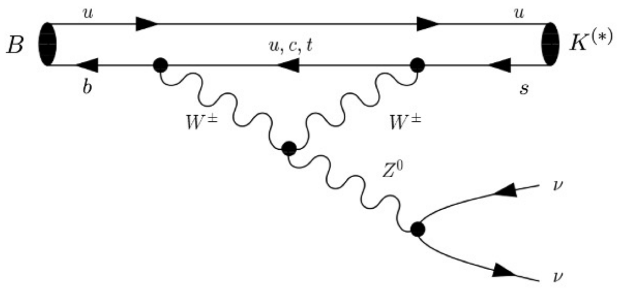




Final prediction SM :

$$\boxed{\mathscr{B}\left(B^\pm \to K^\pm \nu\bar{\nu}\right) = (4.44 \pm 0.30) \times 10^{-6}}$$

D. Becirevic, G. Piazza & O. Sumensari, EPJC '23 [arXiv:2301.06990]



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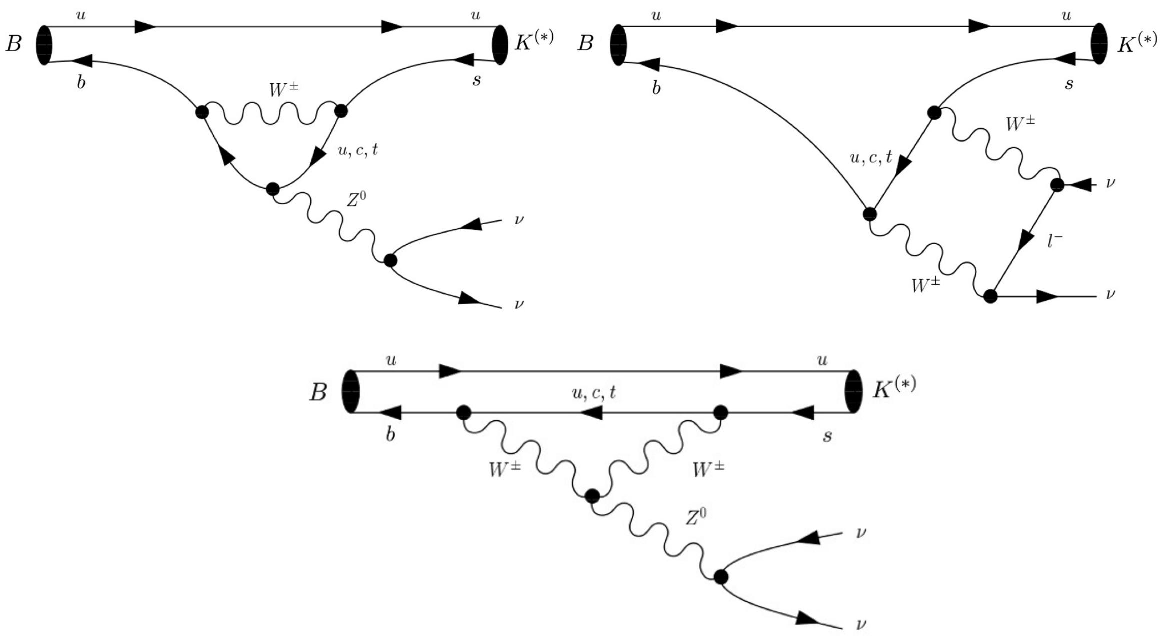

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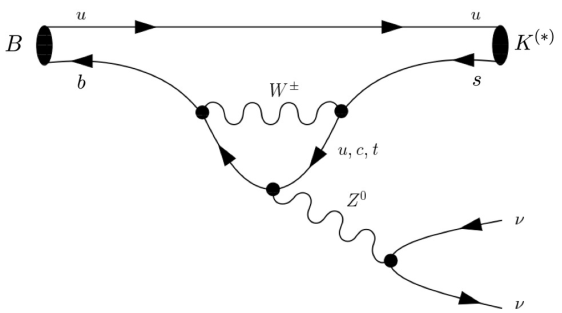

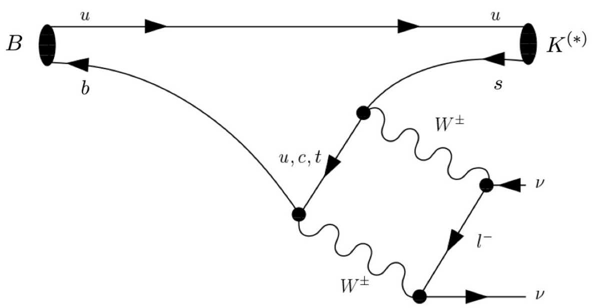

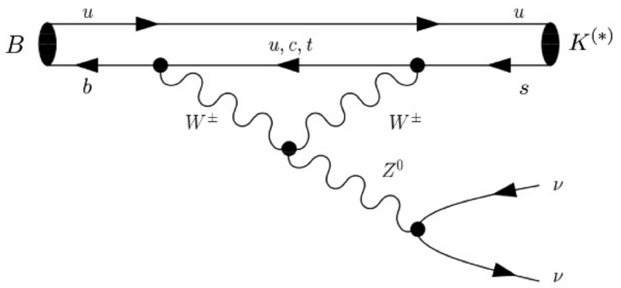

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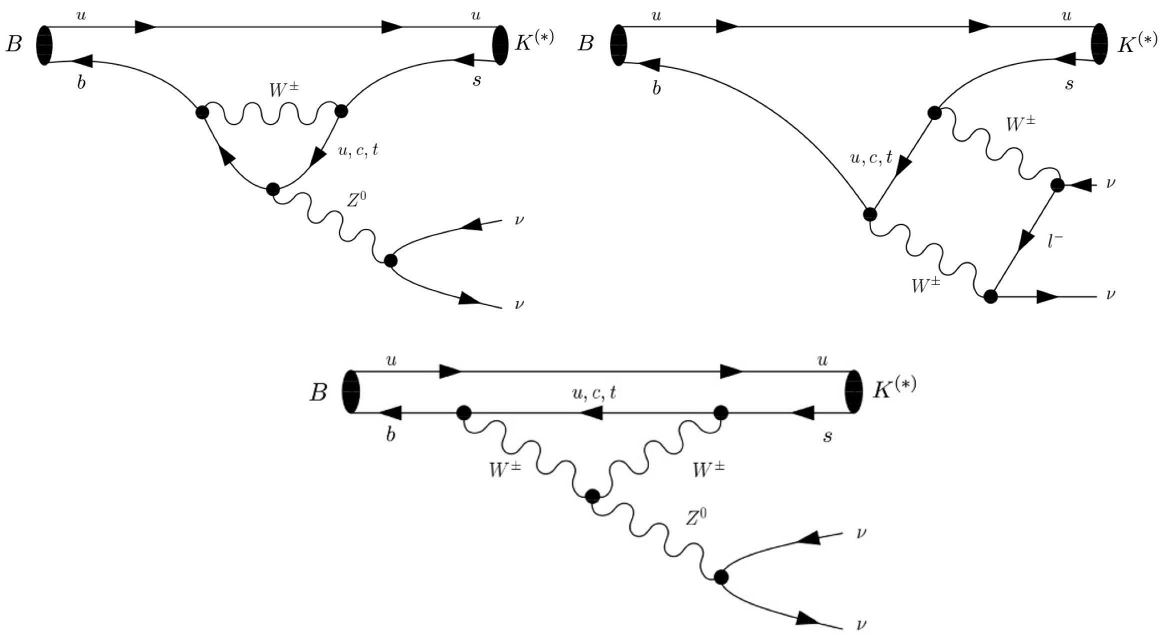

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$\left\{\mathcal{B}(B \to K^* \nu\bar{\nu}) < 2.7 \times 10^{-5}\right.$ **Belle Coll., PRD '17 [1702.03224]** $\left.\right\}$

K → $\pi\nu\nu$ decays

Experiments are giving (or will give) insights on **K^+, K_L (and K_S ?) physics:**

NA62 (K^+): $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$ NA62 Collaboration, JHEP '25 [2412.12015]

KOTO (K_L): $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 2.0 \times 10^{-9}$ at 90% C.L. KOTO Coll., PRL '25 [2411.11237]

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$$\pm 0.04_{\kappa_+} \pm 0.14_\lambda \pm 0.31_A \pm 0.12_{\bar\rho} \pm 0.03_{\bar\eta} \pm 0.05_{m_t} \pm 0.15_{m_c} \pm 0.06_{\alpha_s}$$

Anzivino et al., EPJC '24 [2311.02923] [Kaons@CERN23]

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Anzivino et al., EPJC '24 [2311.02923] [Kaons@CERN23]

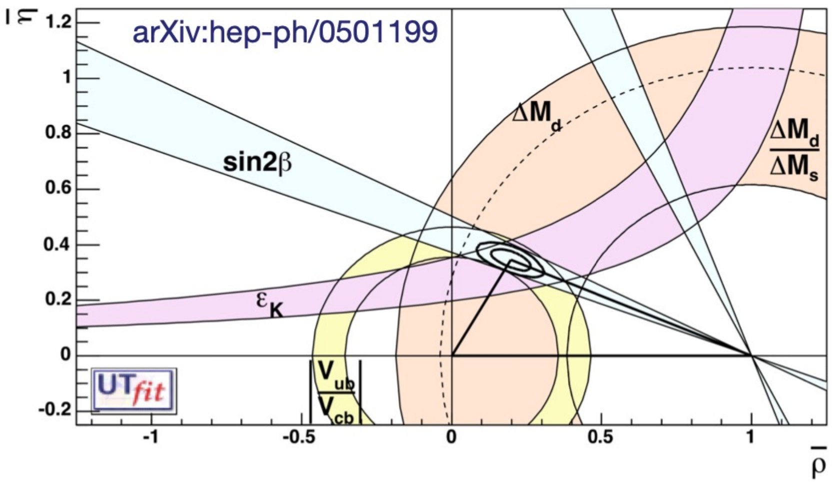
- $$10^{11} \times \mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = 2.87 \pm 0.07_{X_t^{\rm QCD}} \pm 0.01_{X_t^{\rm EW}} \pm 0.02_{\kappa_L}$$
$$\pm 0.15_{\bar{\eta}} \pm 0.15_{A} \pm 0.07_{\lambda} \pm 0.03_{m_t}\,.$$

Anzivino et al., EPJC '24 [2311.02923] [Kaons@CERN23]

Improving precision on the Unitarity Triangle

Marcella Bona[1] Marco Ciuchini[2] Denis Derkach[3] Fabio Ferrari[4,5] Vittorio Lubicz[2,7] Guido Martinelli[6,8] Davide Morgante[9,10] Maurizio Pierini[11] Luca Silvestrini[6] Silvano Simula[2] Achille Stocchi[12] Cecilia Tarantino[2,7] Vincenzo Vagnoni[4] Mauro Valli[6] and Ludovico Vittorio[6,8]

www.utfit.org



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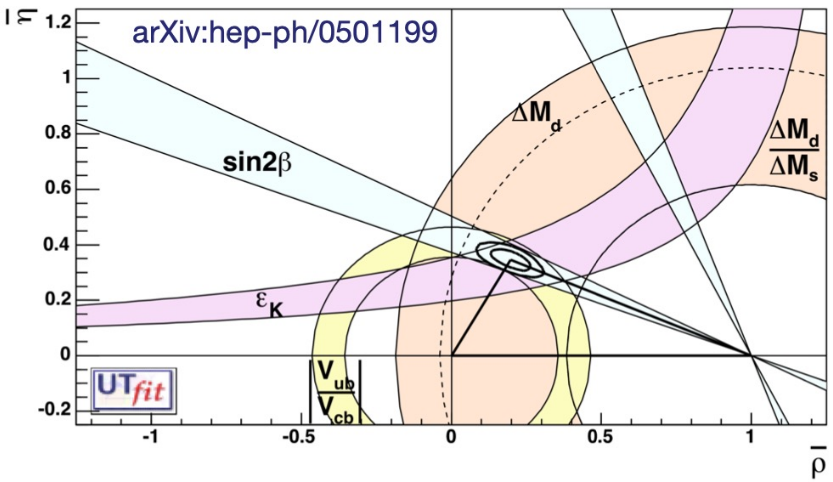

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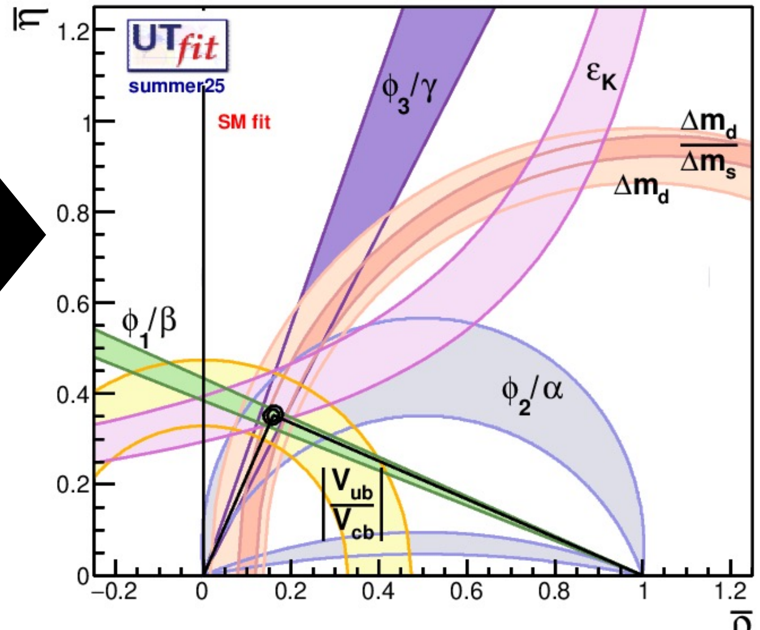

LV's talk @ EPS-HEP 2025

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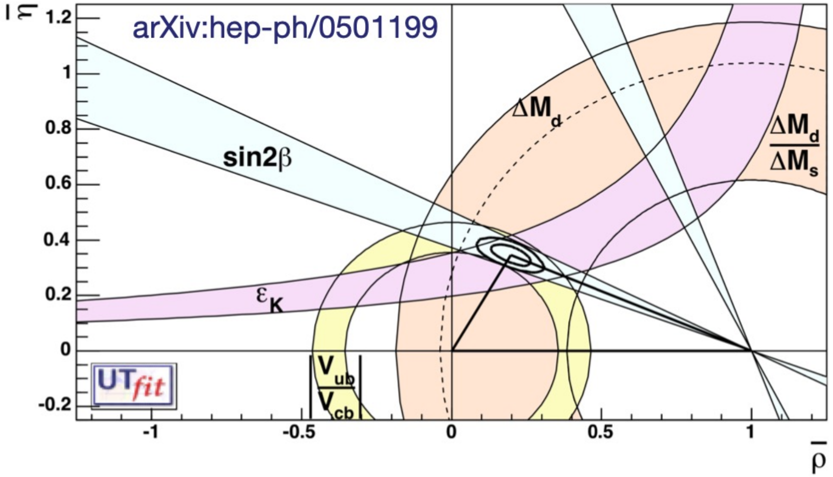

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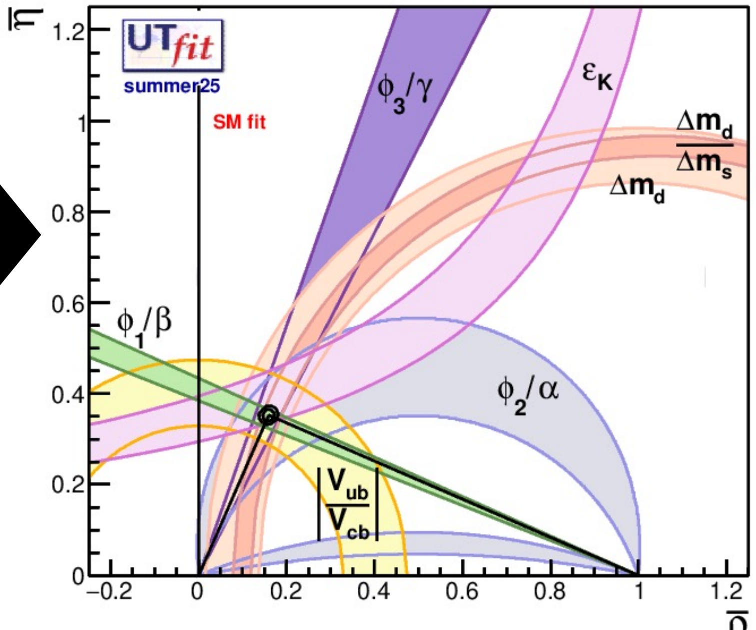

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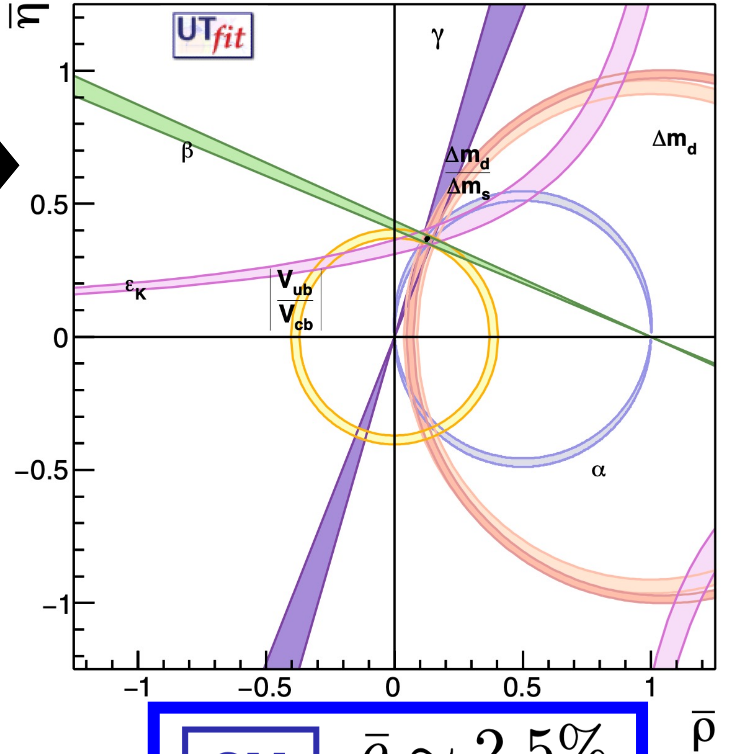

SM fit

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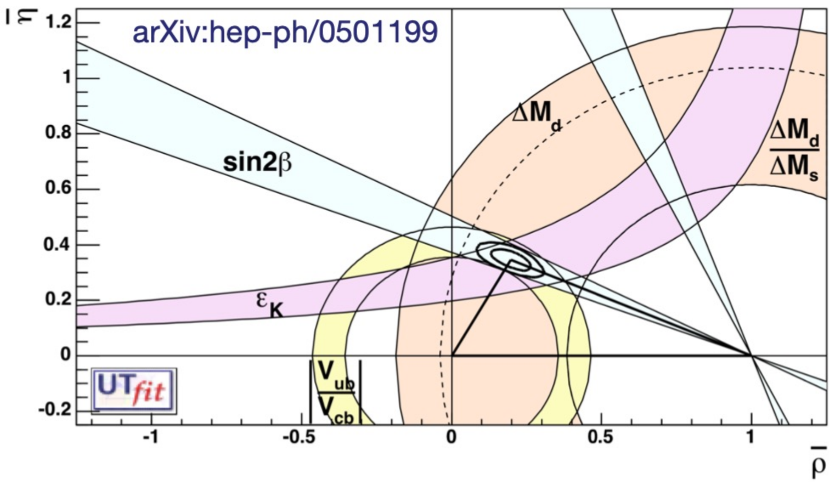
Assumption: 50 ab^{-1} lum. @ Belle II (arXiv:1808.10567)



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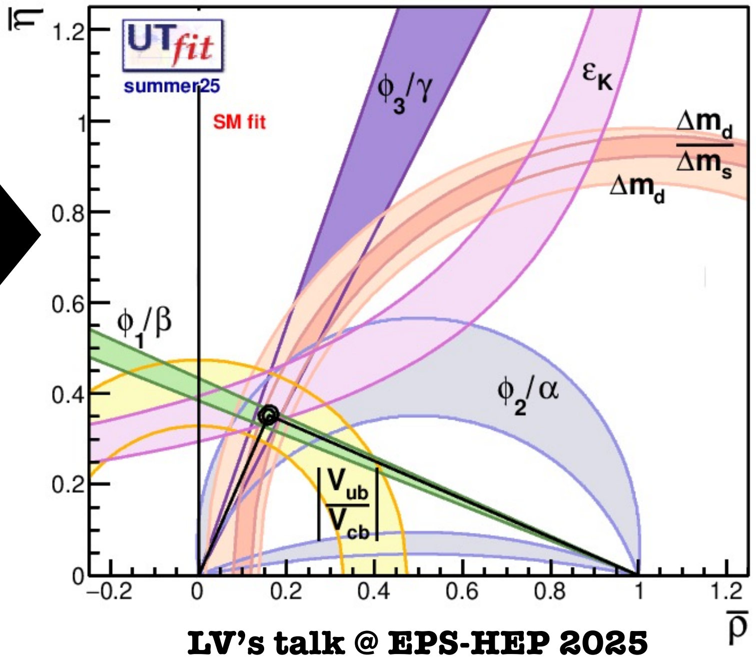

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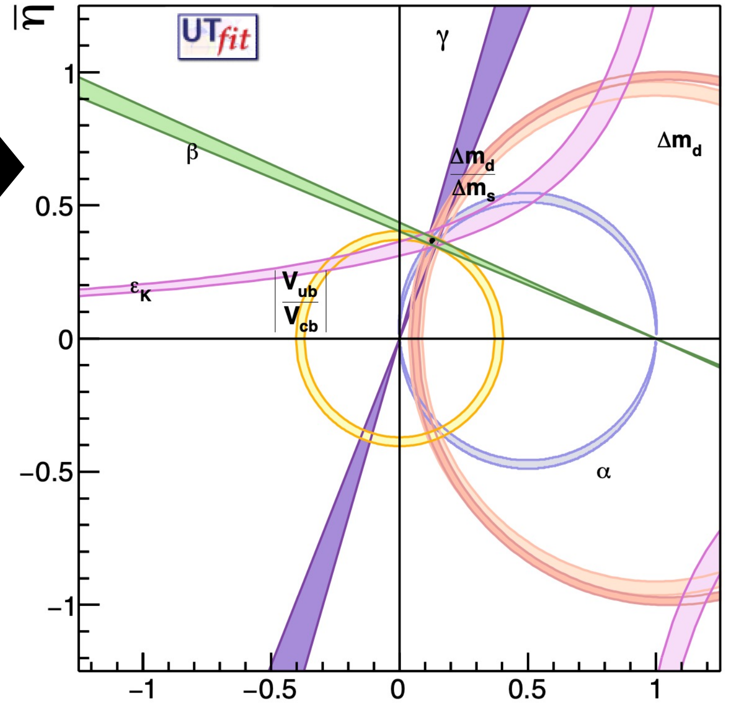

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Conclusions

Many challenges have to be faced from both the theoretical and the experimental points of view in the next few years! To summarize:

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Flavour is the best framework to test indirectly very high energy scales (much higher than the one presently investigated at colliders) ☺

GRAZIE PER LA VOSTRA ATTENZIONE !

BACK-UP SLIDES

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

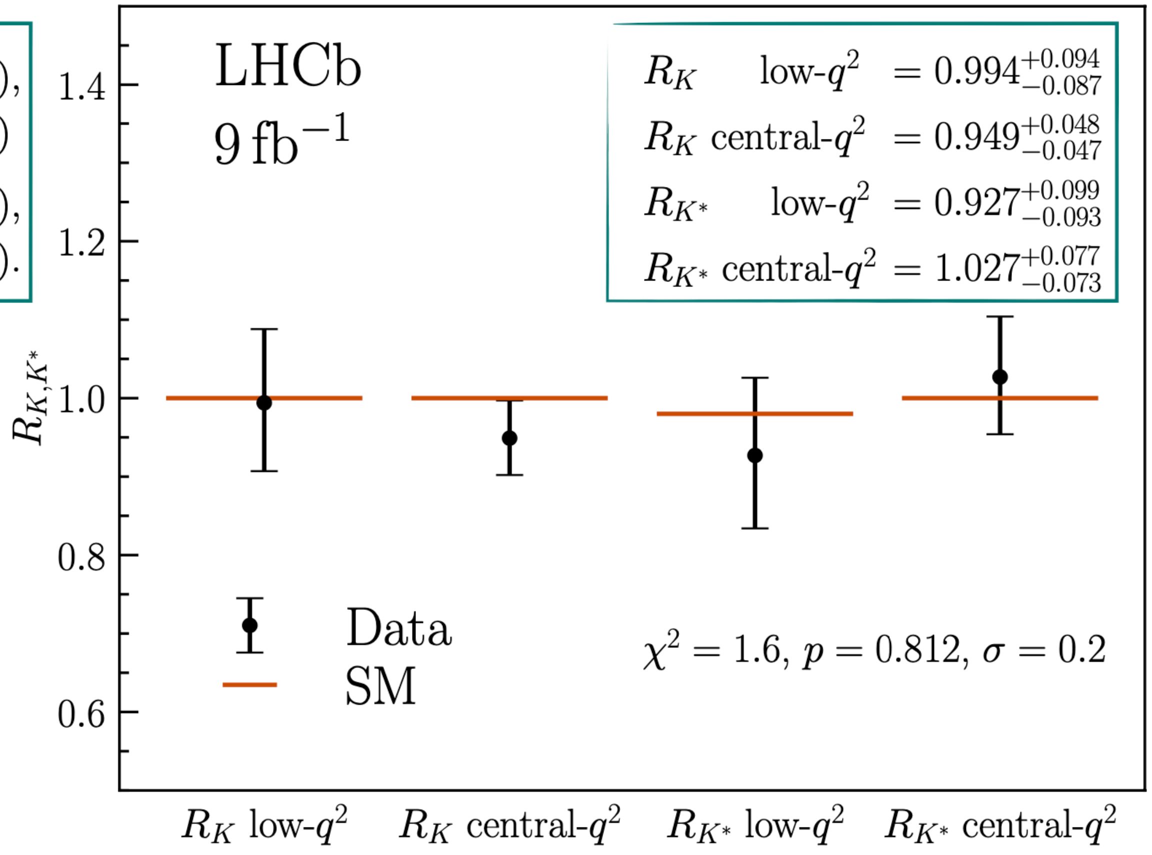
Analysis: results

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



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

The Dispersive Matrix (DM) method

Our goal is to describe the FFs using a novel, non-perturbative and model independent approach *in the whole kinematical region*!

- Pioneering works from S. Okubo [PRD, 3 (1971); PRD, 4 (1971)], C. Bourrely et al [NPB, 189 (1981)] and L. Lellouch [NPB, 479 (1996)]
- New developments in M. di Carlo et al, PRD '21 (2105.02497)

Let us focus on a generic FF *f*: **we will determine f(t) with f(t_i) known at positions t_i (i=1, ..., N)**

$$z(t) = \frac{\sqrt{\frac{t_+ - t}{t_+ - t_-}} - 1}{\sqrt{\frac{t_+ - t}{t_+ - t_-}} + 1}$$

$$t_\pm \equiv (m_B \pm m_D)^2$$

t: momentum transfer

How? Through: - An inner product

$$\langle h_1 | h_2 \rangle = \int_{|z|=1} \frac{dz}{2\pi i z} \bar{h}_1(z) h_2(z)$$

- An auxialiary function

$$g_t(z) \equiv \frac{1}{1 - \bar{z}(t) z}$$

We build up the matrix M of the scalar products of ϕf, g_t, g_{t1}, ..., g_{tN} :

$$\mathbf{M} = \begin{pmatrix} \langle \phi f | \phi f \rangle & \langle \phi f | g_t \rangle & \langle \phi f | g_{t_1} \rangle & \cdots & \langle \phi f | g_{t_n} \rangle \\ \langle g_t | \phi f \rangle & \langle g_t | g_t \rangle & \langle g_t | g_{t_1} \rangle & \cdots & \langle g_t | g_{t_n} \rangle \\ \langle g_{t_1} | \phi f \rangle & \langle g_{t_1} | g_t \rangle & \langle g_{t_1} | g_{t_1} \rangle & \cdots & \langle g_{t_1} | g_{t_n} \rangle \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \langle g_{t_n} | \phi f \rangle & \langle g_{t_n} | g_t \rangle & \langle g_{t_n} | g_{t_1} \rangle & \cdots & \langle g_{t_n} | g_{t_n} \rangle \end{pmatrix}$$

The Dispersive Matrix (DM) method

CENTRAL ISSUE: since **M** contains only inner products, by construction its determinant is semipositive definite

$$\det \mathbf{M} \geq 0 \;\Rightarrow\; f_{\mathrm{lo}}(z) \leq f(z) \leq f_{\mathrm{up}}(z)$$

DISPERSION RELATIONS:

$$0 \leq \langle \phi f | \phi f \rangle \leq \chi(q^2)$$

$$\mathbf{M} = \begin{pmatrix} \boxed{\langle \phi f | \phi f \rangle} & \langle \phi f | g_t \rangle & \langle \phi f | g_{t_1} \rangle & \cdots & \langle \phi f | g_{t_n} \rangle \\ \langle g_t | \phi f \rangle & \langle g_t | g_t \rangle & \langle g_t | g_{t_1} \rangle & \cdots & \langle g_t | g_{t_n} \rangle \\ \langle g_{t_1} | \phi f \rangle & \langle g_{t_1} | g_t \rangle & \langle g_{t_1} | g_{t_1} \rangle & \cdots & \langle g_{t_1} | g_{t_n} \rangle \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \langle g_{t_n} | \phi f \rangle & \langle g_{t_n} | g_t \rangle & \langle g_{t_n} | g_{t_1} \rangle & \cdots & \langle g_{t_n} | g_{t_n} \rangle \end{pmatrix}$$

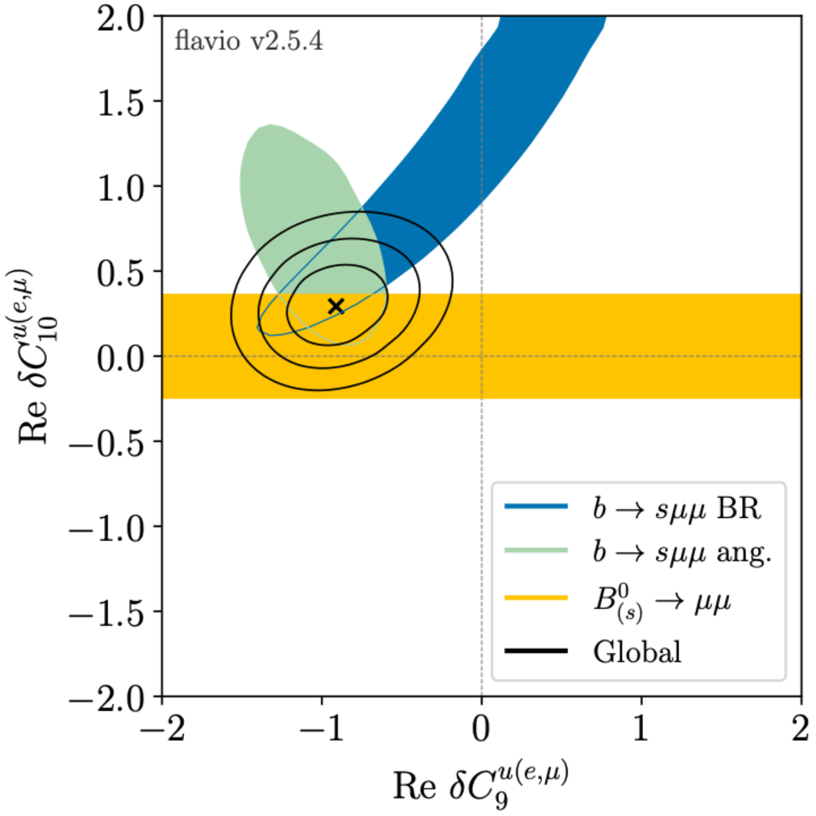
$B_s \to \mu\mu\gamma$ as a golden channel to study NP

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}	$\equiv$	$\delta C_k^{(e)} + \delta C_k^{u(e,\mu)}$
	$\delta C_k^{bs\mu\mu}$	$\equiv$	$\delta C_k^{(\mu)} + \delta C_k^{u(e,\mu)}$

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



E
X
A
M
P
L
E

REMARK: **we are computing these NP shifts assuming,**
as said before, that SM long-distance effects are negligible !!
(See also the global analyses in JHEP '23 [2212.10497], PRD '23 [2212.10516] …)

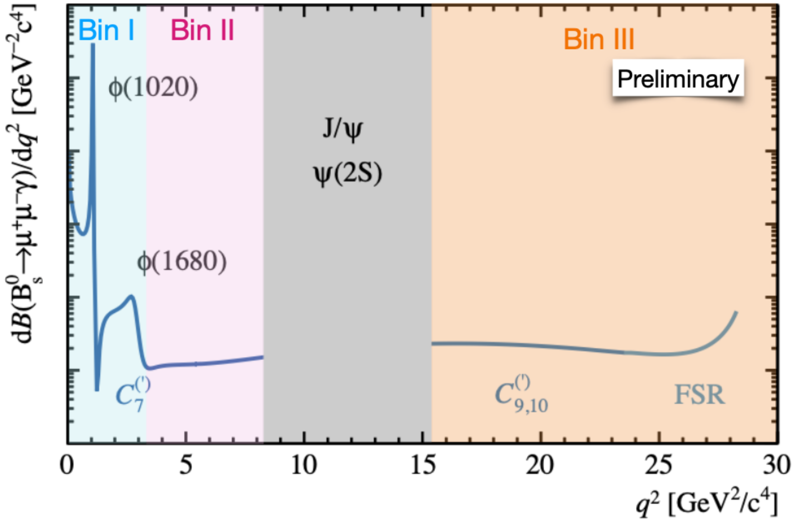
Method I: measure Bs → $\mu\mu\gamma$ with photon reconstruction

Pro: Sensitive to low-q2 region, therefore, to larger set of Wilson coefficients

Con: Photon reconstruction worsen the resolution

Three q² regions:

- Bin I: low-q²
- Bin II: middle-q²
- Bin III: high-q²



Phys.Rev.D70(2004)114028

CERN-THESIS-2020-303

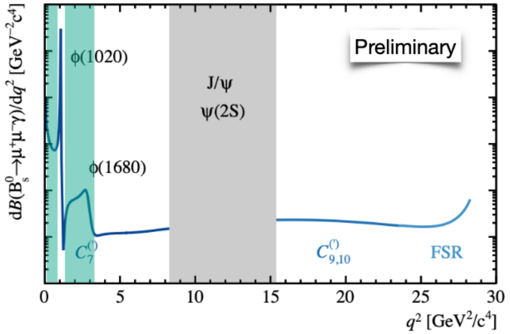
$E_\gamma > 50\mathrm{MeV}/c^2$

FSR = final state radiation

Additionally, Bin I is also studied with a veto on the ϕ-resonance mass:

$m(\mu^+\mu^-)$ = [989.6, 1073.4]MeV/c²

Bin I ϕ-veto: low-q² without ϕ region



q^2 bin	I	II	III
q^2 [GeV^2/c^4]	$[4\,m_\mu^2, 2.89]$	$[2.89, 8.29]$	$[15.37, m^2_{B^0_s}]$
$m(\mu^+\mu^-)$ [GeV/c^2]	$[2\,m_\mu, 1.70]$	$[1.70, 2.88]$	$[3.92, m_{B^0_s}]$
$10^{10}\times\mathcal{B}(B^0_s\to\mu^+\mu^-\gamma)$ [8]	82 ± 15	2.54 ± 0.34	9.1 ± 1.1
Fraction of $B^0_s\to\mu^+\mu^-\gamma$	87%	2.7%	9.8%

Irene Bachiller - Search for the $B^0_s\to\mu^+\mu^-\gamma$ decay at LHCb 9

Unfortunately, the measured BR is not statistically significant in any of the three regions…

Upper limits on BR in the regions I, II and III (see next slides)

I. Bachiller, presentation @ «Workshop on radiative leptonic B decays», Marseille 2024

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

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

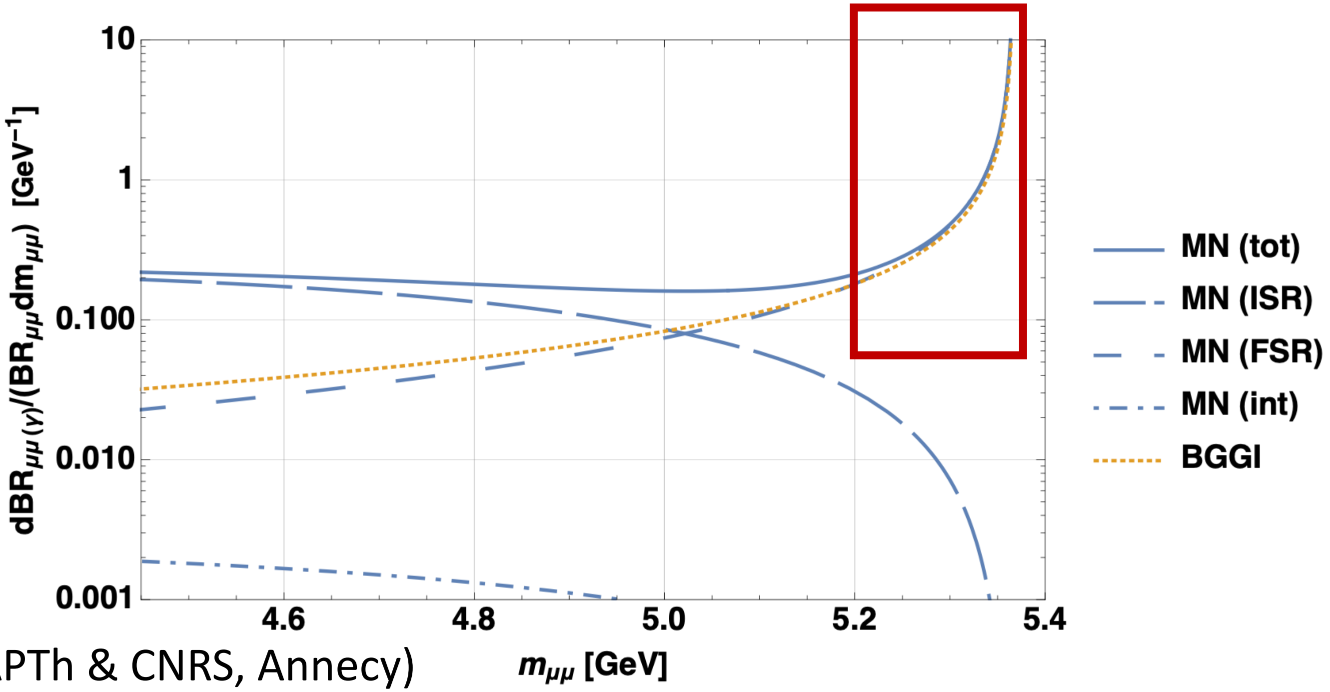
$$B_s^0 \to \mu^+\mu^-\gamma \text{ from } B_s^0 \to \mu^+\mu^-$$

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

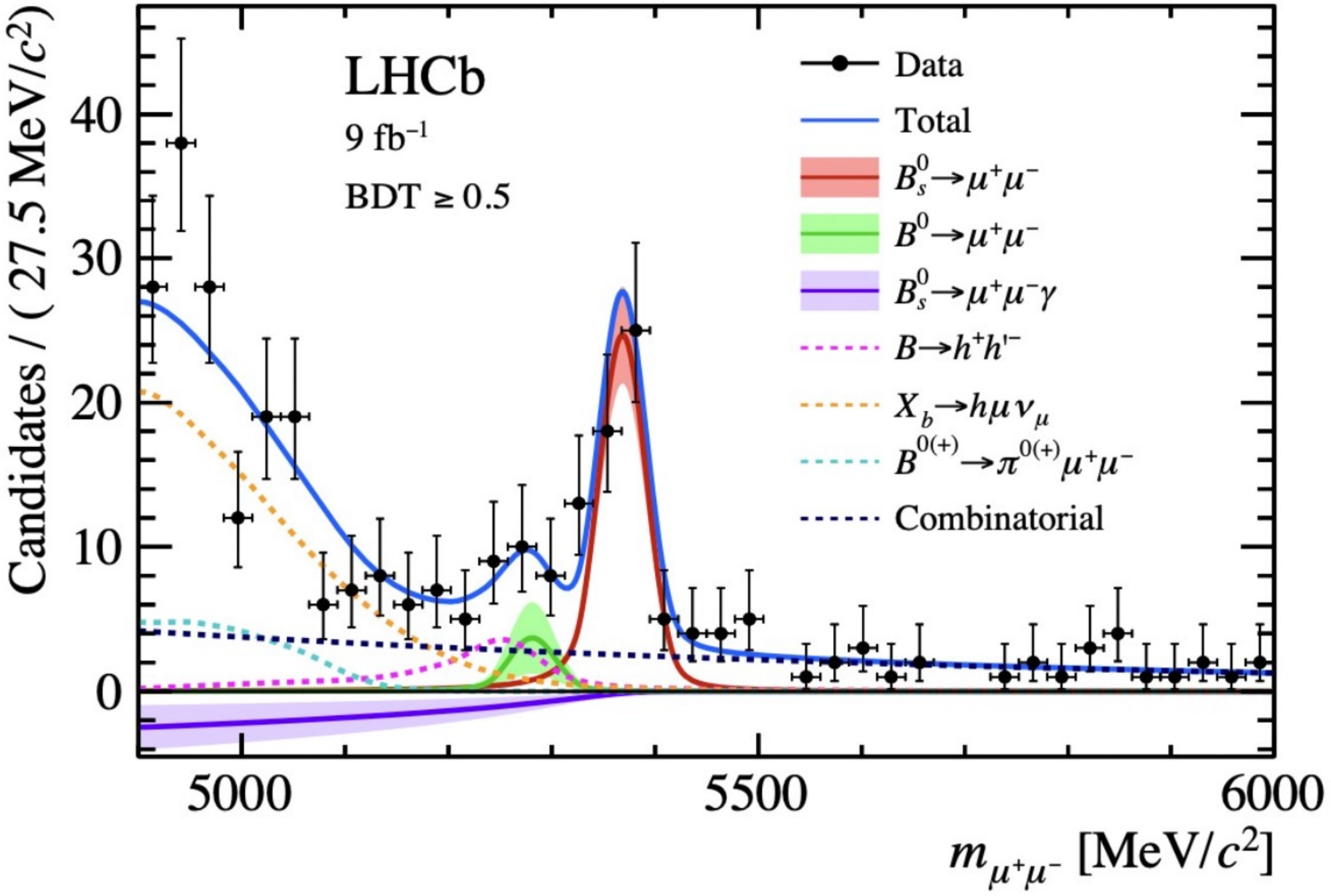
$$\mathcal{B}(B_s^0 \to \mu^+\mu^- + n\gamma) \textbf{ VS } \mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)$$



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 !!

$B_s \to \mu\mu\gamma$ 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 $B_s \to \mu\mu\gamma$-signal uncertainty will be dominated by the sheer amount of data collected

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

3. ***Theoretical uncertainties:***
   - *GNSV FFs with shrinked uncertainties, i.e. O(5%) errors, and KMN tensor FFs with O(20%) uncertainties*
   - *assumption: broad charmonia play an entirely negligible role at high-q2*

Recall that we need to resolve $\delta C_9^{(\mu)} / C_9^{(\mu),\mathrm{SM}} \simeq 15\%$ **!!**

Motivated by precision on $D_s \to \gamma$ FFs as from the lattice study **PRD '23 (2306.05904)**, confirmed by the $B_s \to \gamma$ results in **PRD '24 (2402.03262)**

B → $K\nu\nu$ as the fundamental link among $b \to c$ and $b \to$ s

b → s$\nu\nu$ is theoretically cleaner than b → s$\mu\mu$: it is not affected by charm-loop effects !!

$$\mathcal{O}_L^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j\right) \quad C_L^{\mathrm{SM}} = -6.32(7)$$

$$\mathcal{O}_R^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_R\gamma_\mu b_R\right)\left(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j\right) \quad C_R^{\mathrm{SM}} = 0$$

Buchalla & Buras, NPB '93
Misiak & Urban, arXiv:hep-ph/9901278
Buchalla & Buras, arXiv:hep-ph/9901288
Brod, Gorbahn & Stamou, arXiv:1009.0947

Major sources of uncertainty:

1. Value of |Vcb| (due to CKM suppression)
2. Determination of hadronic FFs

Final prediction

$$\boxed{\mathcal{B}\left(B^\pm \to K^\pm \nu\bar{\nu}\right) = (4.44 \pm 0.30) \times 10^{-6}}$$

Final prediction

$$\boxed{\mathcal{B}\left(B^\pm \to K^{\pm *} \nu\bar{\nu}\right) = (9.8 \pm 1.4) \times 10^{-6}}$$

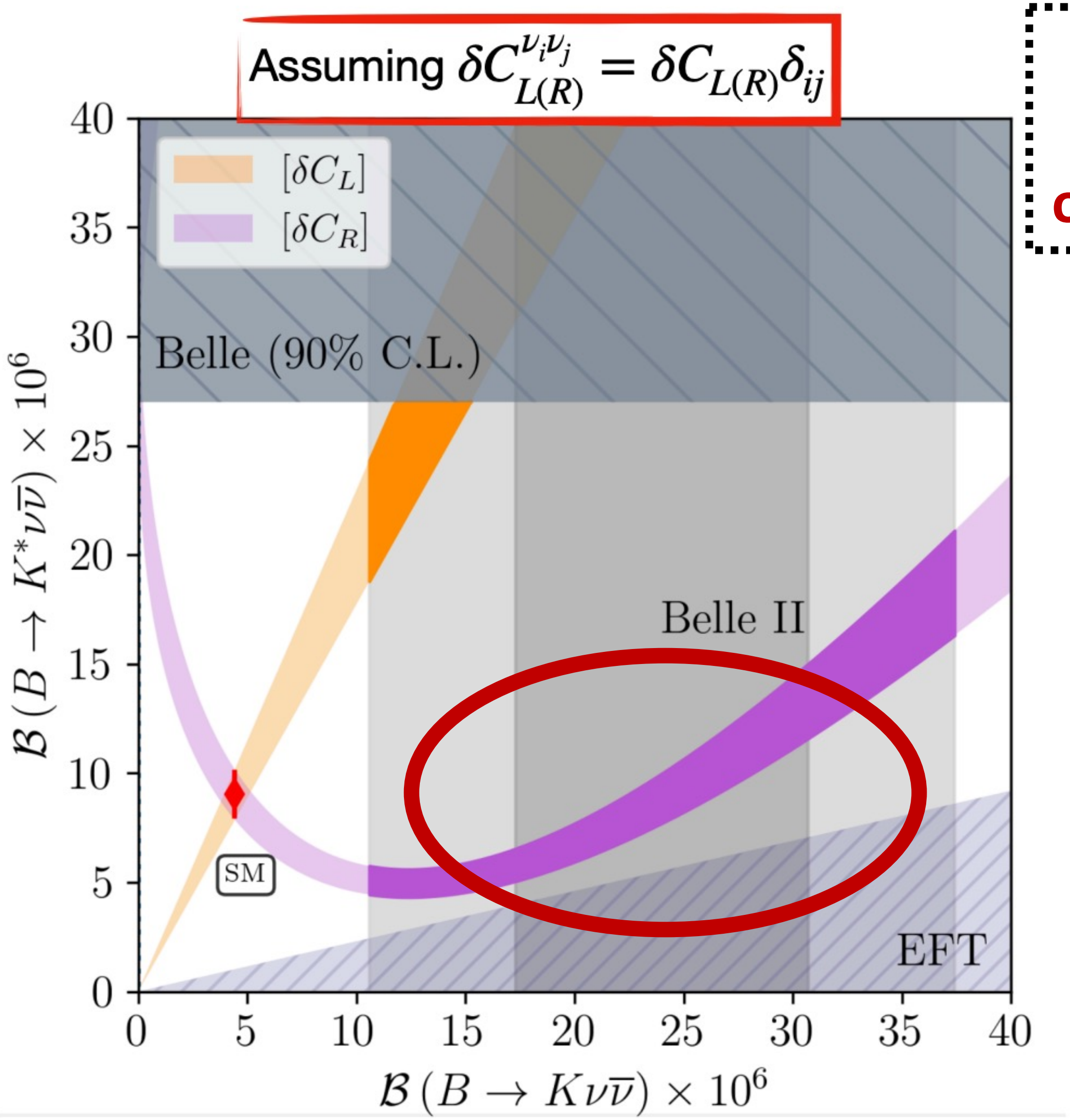
D. Becirevic, G. Piazza & O. Sumensari, EPJC '23 [arXiv:2301.06990]

to be compared with

$$\boxed{\mathcal{B}\left(B^+ \to K^+ \nu\bar{\nu}\right)\Big|_{\mathrm{Belle-II}} = (2.4 \pm 0.7) \times 10^{-5}}$$

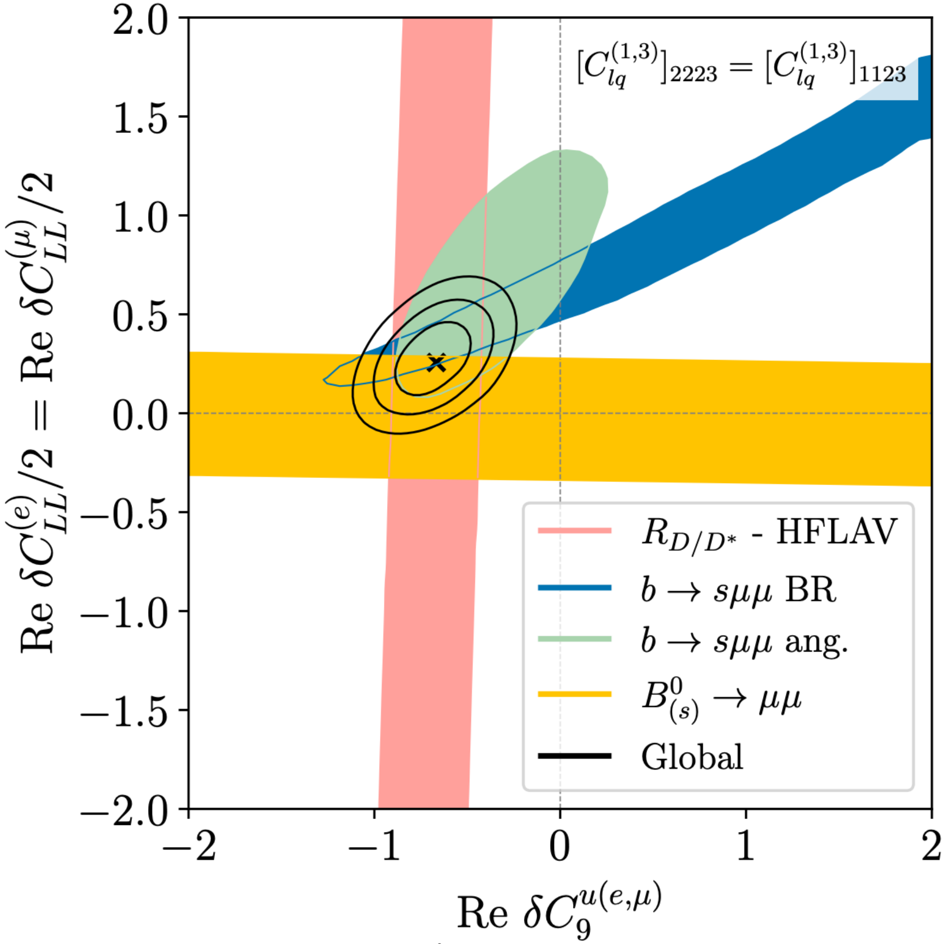
A. Glazov, plenary talk EPS-HEP2023 Conference, Aug 20-25, 2023

B → Kυυ as the fundamental link among b → c and b → s



L. Allwicher et al., arXiv:2309.02246

This kind of channels is important for SMEFT analyses, since **B → Kυυ may influence b → s observables (with charged leptons) and b → c ones !**



D. Guadagnoli et al, JHEP '23 [2308.00034]

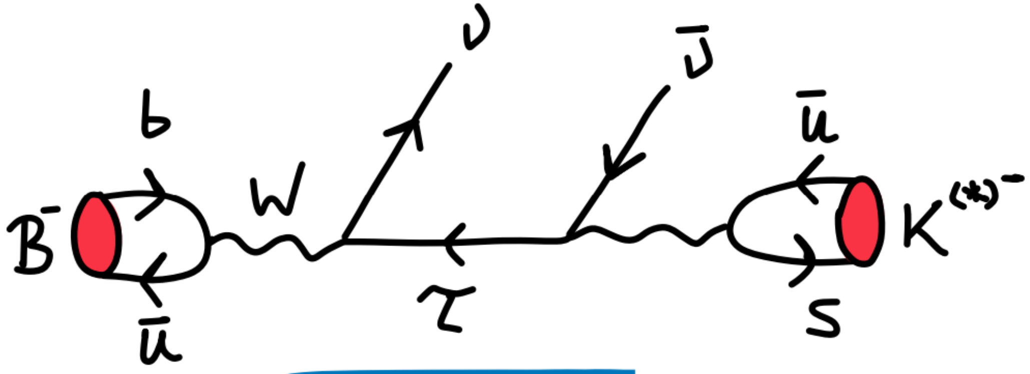
Light-lepton universal NP scenario [without B → Kυυ data]

Tree-level contribution

$B^\pm \to K^{\pm(*)}\nu\bar{\nu}$

J. F. Kamenik & C.Smith, arXiv:0908.1174

Charged meson decay modes have a tree-level contribution from the annihilation to an intermediate τ



$\boxed{m_B > m_\tau > m_{K^{(*)}}}$

Using the narrow width approximation

$$\mathscr{B}\left(B^+ \to K^{(*)+}\nu\bar{\nu}\right) \sim \mathscr{B}\left(B^+ \to \tau^+\nu\right)\mathscr{B}\left(\tau^+ \to K^{(*)+}\bar{\nu}\right)$$

$$\boxed{\frac{\mathscr{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)_{\text{tree}}}{\mathscr{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)_{\text{loop}}} \simeq 14\,\%\,(11\%)}$$

Non negligible contribution!

Belle-II can in principle disentangle these two contributions

Basics of the Unitarity Triangle analysis

The Cabibbo-Kobayashi-Maskawa (CKM) matrix described the mixing amon quarks (with different electric charges): it is a unitary 3x3 matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad V_{CKM}^{\dagger} V_{CKM} = I$$

Wolfenstein parametrization (L. Wolfenstein, PRL 51 (1983) 1945-1947):

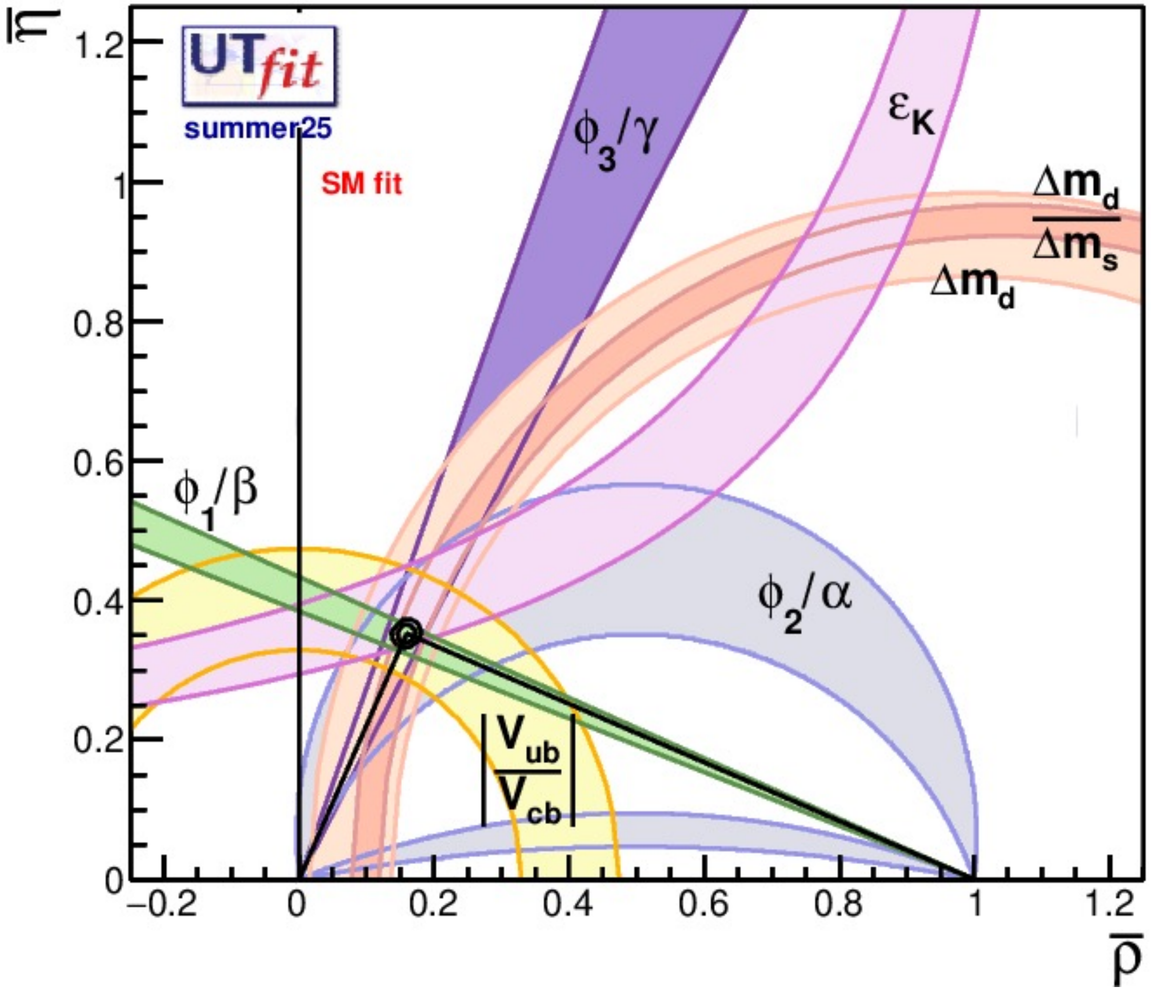
$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

By exploiting the property of unitarity:

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0 \quad \Longrightarrow$$

Triangle in the complex $(\bar{\rho}, \bar{\eta})$ plane

UTA within the SM: results



Example of relations to understand the coloured bands:

$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1-\frac{\lambda^2}{2}}\sqrt{\bar{\rho}^2+\bar{\eta}^2}$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left(\frac{\lambda}{1-\frac{\lambda^2}{2}}\right)^2 \left[(1-\bar{\rho})^2+\bar{\eta}^2\right]$$

Fit results:

$\bar{\rho}$ = **0.159 ± 0.009**

$\bar{\eta}$ = **0.353 ± 0.008**

λ = **0.2250 ± 0.0006**

A= **0.827 ± 0.008**