Rare B and K decays

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IP2I, Lyon

2nd mini workshop

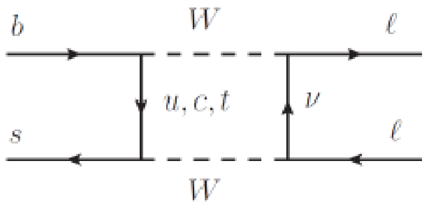
10 October 2023

Indirect searches of New Physics (NP) via Flavour Changing Neutral Current (FCNC) processes

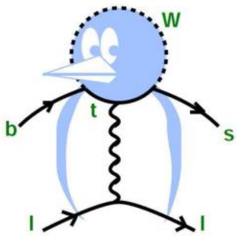
- Rare *B* decays: $b \to s$ processes
- Rare *K* decays: $s \to d$ processes

Both loop suppressed in the SM

Box diagram:



Penguin diagram:



$b \to s$ transitions

- Abundant data already available (from BaBar, Belle, LHCb) & more to come (Belle II, LHCb upgrade, …)
- Good control over long-distance strong interactions (m_b much larger than Λ_{QCD})
- Although tensions in theoretically clean observables R_K, R_{K^*} and BR($B_s \to \mu\bar{\mu}$) gone there are still deviations in branching ratios and angular observables of $B \to K^*\mu\bar{\mu}$, $B_s \to \phi\mu\bar{\mu}$ and $B \to K\mu\bar{\mu}$

Lepton flavour universality in $B \to K\ell^+\ell^-$:

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

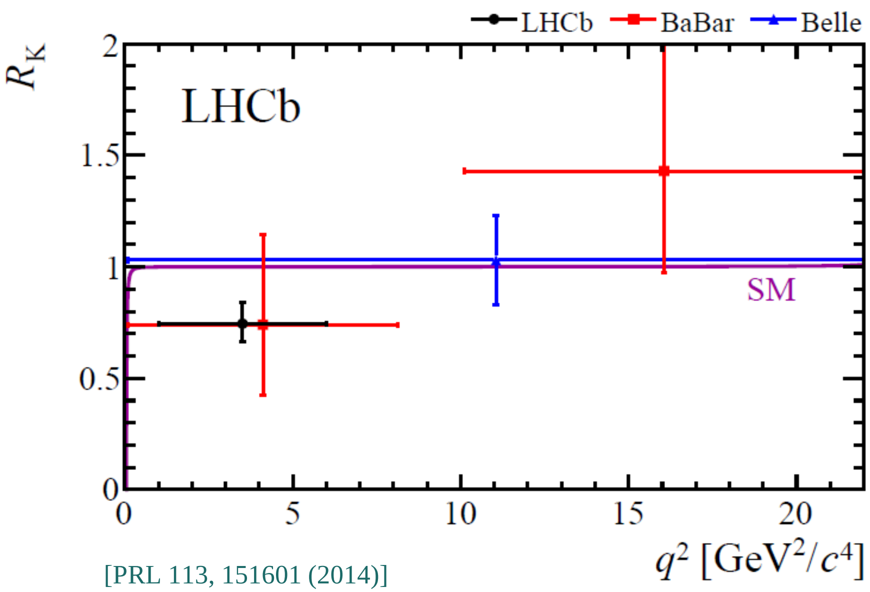
Hiller, Kruger,
Phys. Rev. D69 (2004) 074020

- Hadronic uncertainties cancel out

$\Longrightarrow$ *theoretically very clean $\mathcal{O}(1\%)$*

Jun. 2014

LHCb (1 fb^{-1})
2.6σ in[1-6] GeV^2
of R_K



[PRL 113, 151601 (2014)]

$$R_K^{\mathrm{SM}}([1.1, 6.0]\ \mathrm{GeV}^2) = 1.006 \pm 0.004$$

$$R_K^{\mathrm{exp}}([1.1, 6.0]\ \mathrm{GeV}^2) = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$\to 2.6\sigma$ tension

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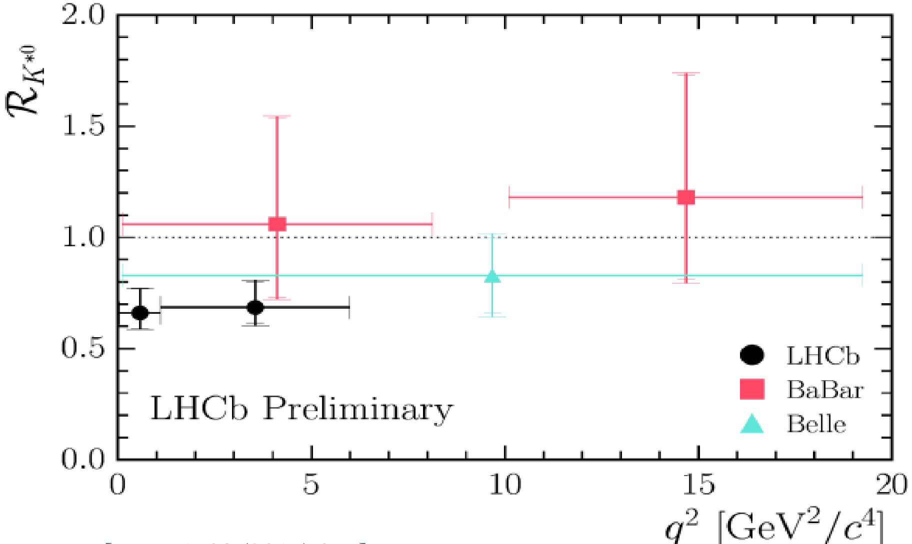

[JHEP 1708 (2017) 055]

$R_{K^*}^{\mathrm{SM,bin\ 1}} = 0.906 \pm 0.020_{\mathrm{QED}} \pm 0.020_{\mathrm{FF}}$

$R_{K^*}^{\mathrm{SM,bin\ 2}} = 1.000 \pm 0.010_{\mathrm{QED}}$

[Bordone, Isidori, Pattori, 1605.07633]

$R_{K^*}^{\mathrm{exp,bin\ 1}} = 0.660^{+0.110}_{-0.070}$ (stat) ± 0.024 (syst)

$R_{K^*}^{\mathrm{exp,bin\ 2}} = 0.685^{+0.113}_{-0.069}$ (stat) ± 0.047 (syst)

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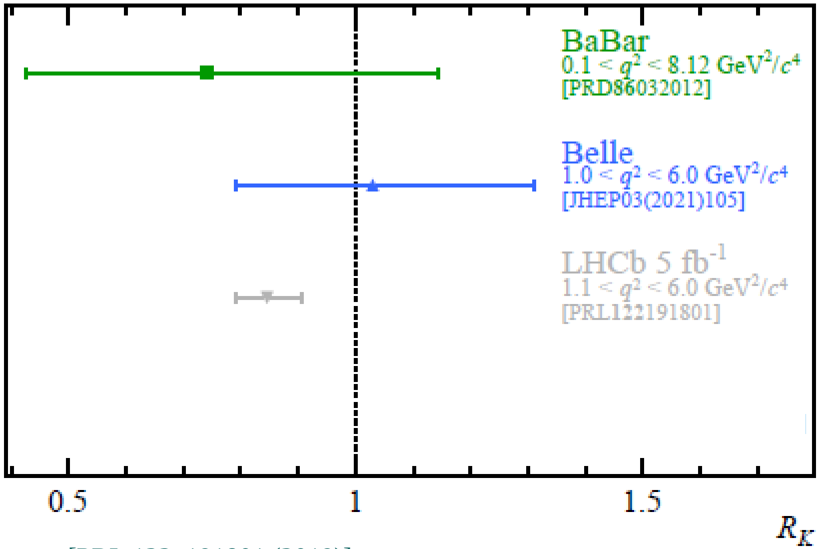

[PRL 122, 191801 (2019)]

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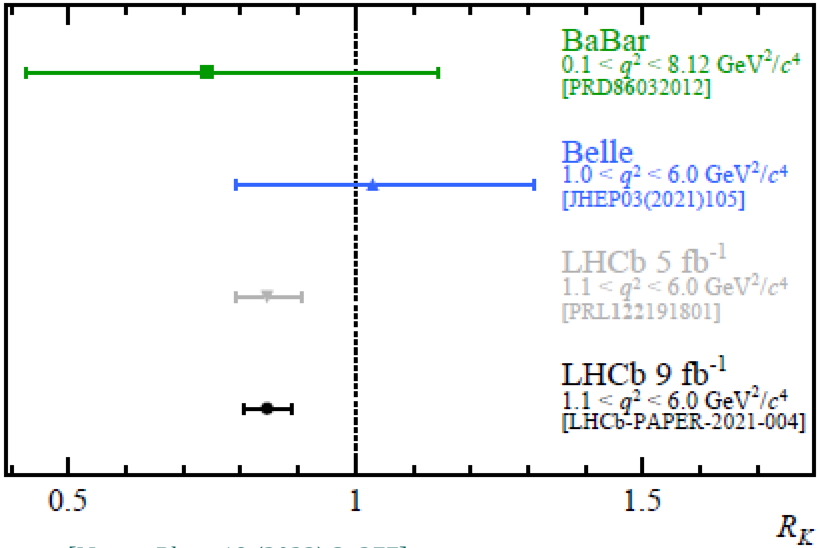

[Nature Phys. 18 (2022) 3, 277]

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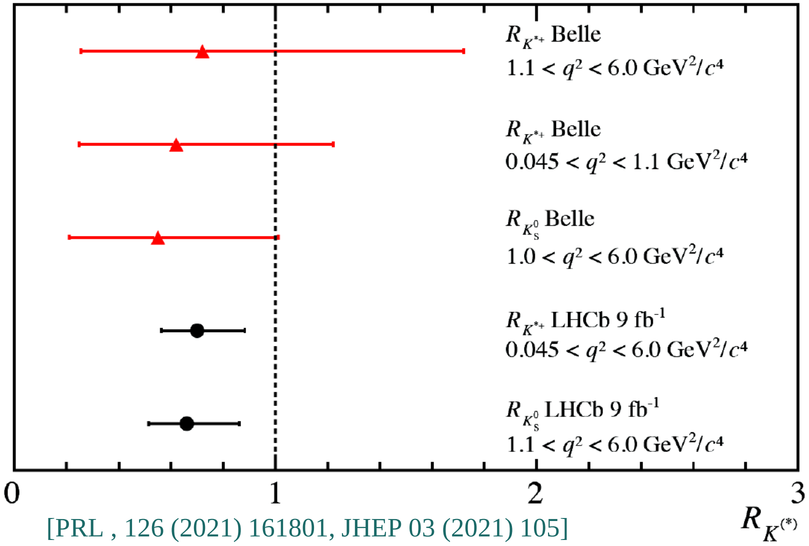

[PRL , 126 (2021) 161801, JHEP 03 (2021) 105]

$B^+ \to K^{*+}\ell^+\ell^-$ and $B^0 \to K_S^0\,\ell^+\ell^-$

$$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(stat)^{+0.03}_{-0.04}(syst)$$

$$R_{K_S^0} = 0.66^{+0.20}_{-0.15}(stat)^{+0.02}_{-0.04}(syst)$$

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- More than 4σ significance for New Physics

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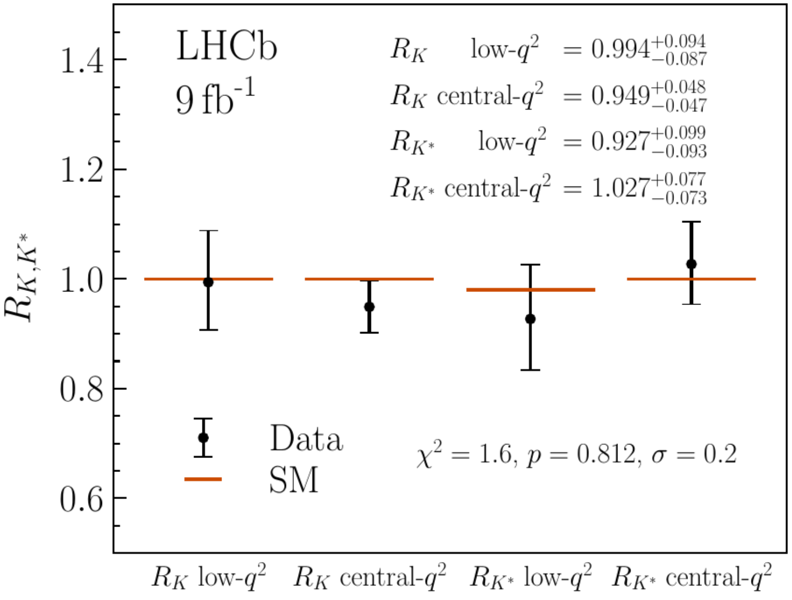
December 2022



- Compatible with SM with a simple χ^2 test on 4 measurement at 0.2 σ

The results presented here differ from previous LHCb measurements of R_K [32] and R_{K^*} [29]. For R_K central-q^2, the difference is partly due to the use of tighter electron identification criteria and partly due to the modeling of the residual misidentified hadronic backgrounds; statistical fluctuations make a smaller contribution to the difference since the same data are used as in Ref. [32].

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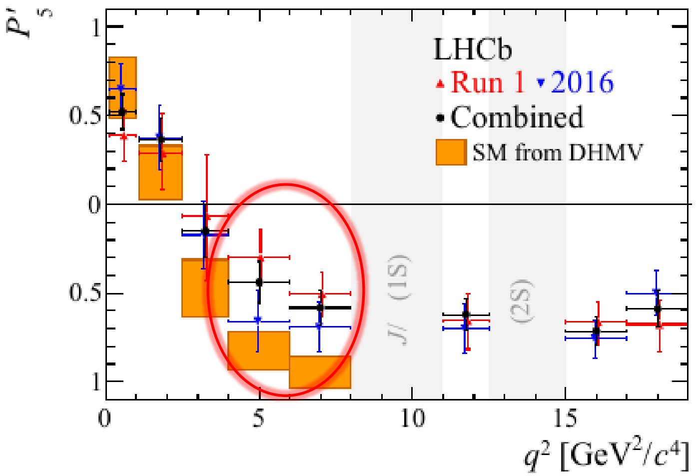
- Hadronic uncertainties cancel out

⟹ *theoretically very clean $\mathcal{O}(1\%)$*

December 2022

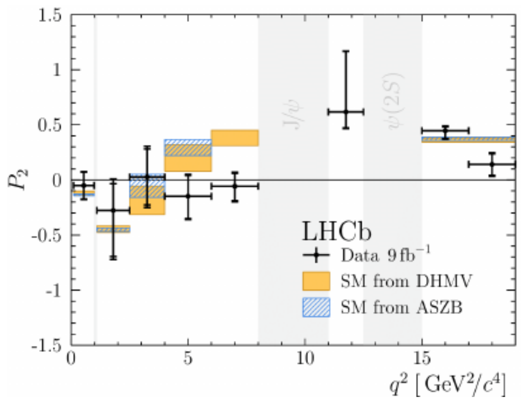
Several deviations ("anomalies") with respect to the SM predictions in $b \to s\mu\mu$ measurements

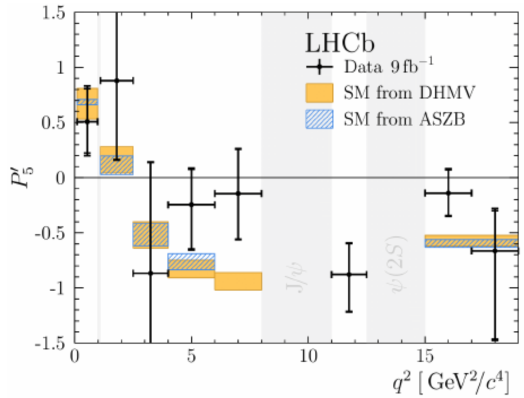
- P_5' ($B \to K^* \mu^+ \mu^-$): Long standing tension since 2013
  - 2020 LHCb update with 4.7 fb^{-1} [PRL 125, 011802 (2021)]



- ➢ ≈2.9σ local tension
  ⟶ significance depends on estimation of hadronic contributions

- First measurement of $B^+ \to K^{*+} \mu^+ \mu^-$ angular observables
  - full Run 1 and Run 2 dataset with 9 fb^{-1} [PRL 126, 161802 (2021)]

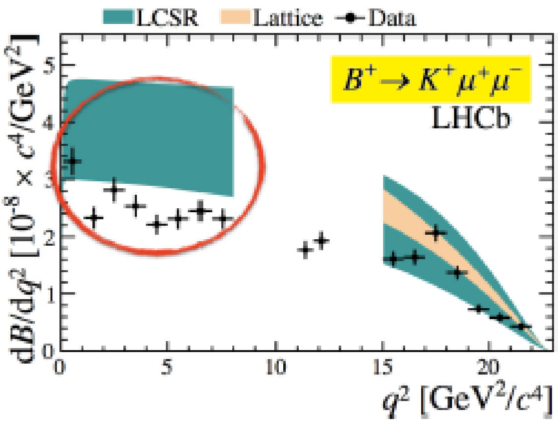


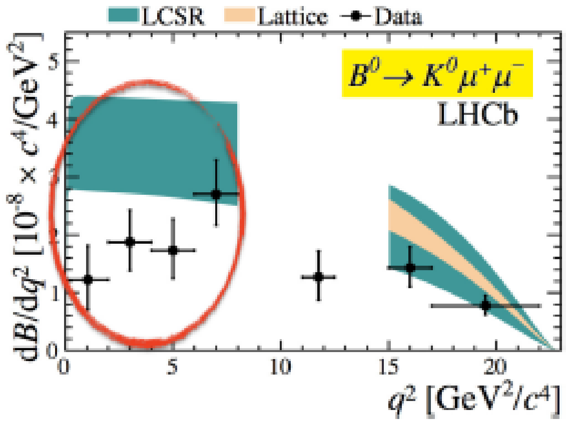


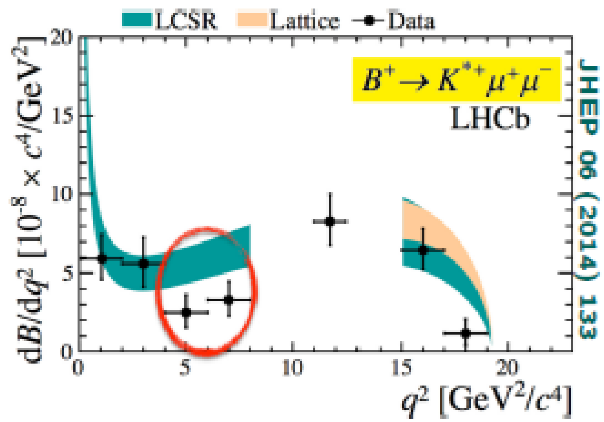
- ➢ overall results confirm the trend of tension with respect to the SM

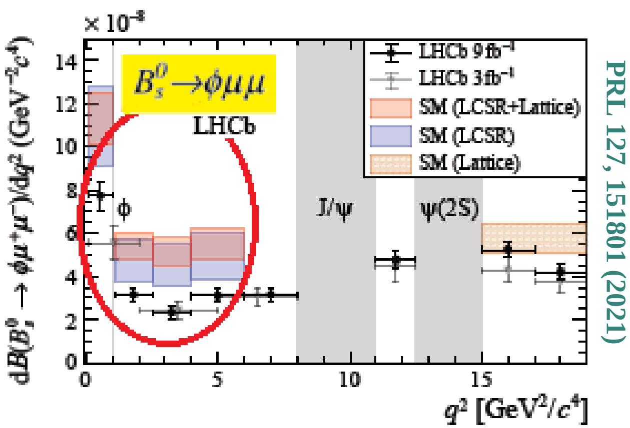
Several deviations (“anomalies”) with respect to the SM predictions in $b \to s\ell\ell$ measurements

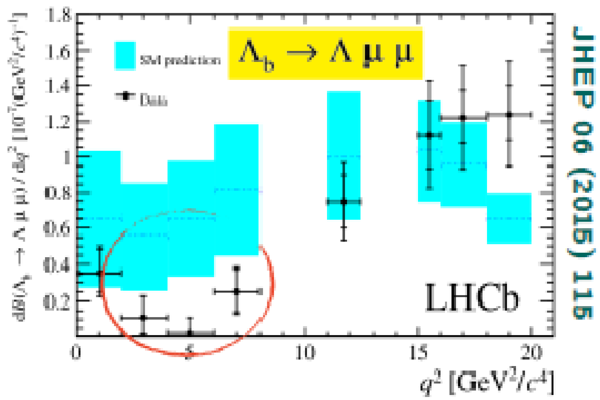
- Branching fractions











- Measurements below SM predictions with $\sim 2-3\sigma$ significance
- Large theory uncertainties (several form factors involved)

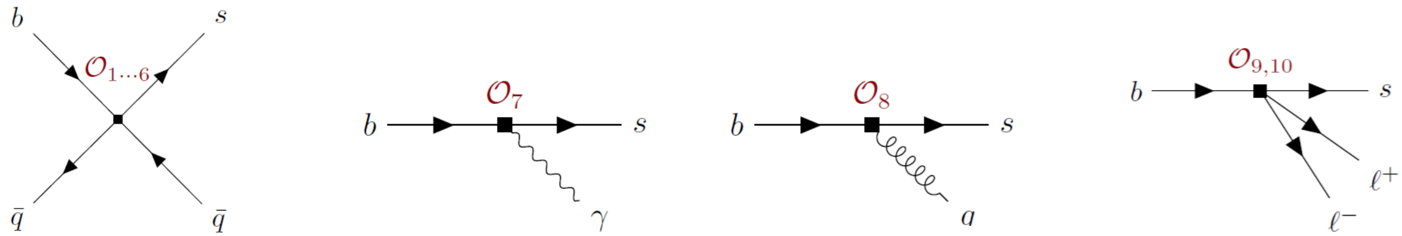
Theoretical Framework

Theoretical framework: Weak Effective Hamiltonian

Separation between low and high energies using Operator Product Expansion

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big(\sum_{i=1\cdots 10,S,P} \big(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)\big)\Big)$$

4-quark operators | electromagnetic dipole operator | chromomagnetic dipole operator | semileptonic operators



$\mathcal{O}_{1,2} \propto [\bar{s}\Gamma_\mu c]\,[\bar{c}\Gamma_\mu b]$

$\mathcal{O}_{3\cdots6} \propto [\bar{s}\Gamma_\mu b][\sum \bar{q}\Gamma^\mu q]$

$\mathcal{O}_7 \propto [\bar{s}\sigma_{\mu\nu}P_R b]\, F^{\mu\nu}$

$\mathcal{O}_8 \propto [\bar{s}\sigma^{\mu\nu}T^a P_{R(L)} b]\, G^a_{\mu\nu}$

$\mathcal{O}_9^\ell \propto [\bar{s}\gamma_\mu P_L b][\bar{\ell}\gamma^\mu \ell]$

$\mathcal{O}_{10}^\ell \propto [\bar{s}\gamma_\mu P_L b][\bar{\ell}\gamma^\mu\gamma_5 \ell]$

Most relevant for $b \to s\ell\ell$: O_7, O_9, O_{10}; in the SM: $C_7 \simeq -0.3,\quad C_9 \simeq 4,\quad C_{10} \simeq -4$

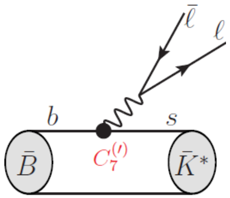
Additional operators: Chirality flipped (O_i'), (pseudo)scalar (O_S and O_P)

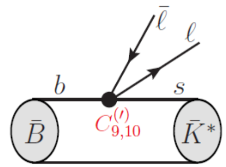
- Wilson coefficients $C_i \to C_i^{\rm SM} + \delta C_i^{\rm NP}$:
  perturbative, short-distance physics (q^2 independent), well-known in the SM
- Matrix elements of local operators:
  non-perturbative, long-distance physics (q^2 dependent), main source of uncertainty

Matrix elements for $B \to M\ell\ell$ ($M = K, K^*, \phi$)

Effective Hamiltonian has two parts: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm sl} + \mathcal{H}_{\rm eff}^{\rm had}$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=7,9,10,S,P} C_i^{(\prime)} \mathcal{O}_i^{(\prime)} \Big]$$





$$\langle M\ell\ell|\mathcal{H}_{\rm eff}^{\rm sl}|B\rangle \propto \mathcal{A}_V^\mu\, \bar u_\ell \gamma_\mu v_\ell + \mathcal{A}_A^\mu\, \bar u_\ell \gamma_\mu\gamma_5 v_\ell + \mathcal{A}_S\, \bar u_\ell v_\ell + \mathcal{A}_P\, \bar u_\ell \gamma_5 v_\ell$$

local contributions:

$$\mathcal{A}_V^\mu = -\frac{2im_b}{q^2} C_7 \langle M|\bar s\, \sigma^{\mu\nu} q_\nu\, P_R\, b|B\rangle + C_9 \langle M|\bar s\, \gamma^\mu\, P_L\, b|B\rangle$$

$$\mathcal{A}_A^\mu = C_{10} \langle M|\bar s\, \gamma^\mu\, P_L\, b|B\rangle$$

$$\mathcal{A}_{S,P} = C_{S,P} \langle M|\bar s\, P_R\, b|B\rangle$$

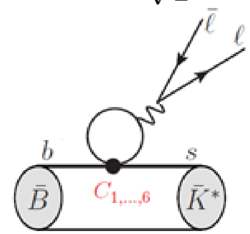
- $M = K$: 3 form factors
- $M = K^*, \phi$: 7 form factors

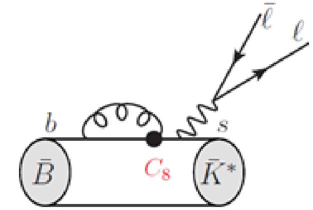
Determined by **Lattice QCD** (high q^2), **Light-Cone Sum Rules** (low q^2) and **combined fit of LCSR + Lattice** (low + high q^2)

($q^2 \equiv$ dilepton invariant mass squared)

Ball et al' '04; Khodjamirian et al. '10; HPQCD '13; Altmannshofer et al. '14; Bharucha et al. '15; MILC '15 ; Horgan et al. '15; Gubernari et al. '18

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=1\ldots6} C_i^{(\prime)} \mathcal{O}_i^{(\prime)} + C_8 \mathcal{O}_8 \Big]$$





$$\langle M\ell\ell|\mathcal{H}_{\rm eff}^{\rm had}|B\rangle \propto \mathcal{N}^\mu \bar u_\ell \gamma_\mu v_\ell$$

non-local contributions:

$$\mathcal{H}^\mu = \frac{-16i\pi^2}{q^2} \sum_{i=1,\ldots,6,8} C_i \int dx^4 e^{iq\cdot x} \langle M|T\{j_{\rm em}^\mu(x), O_i(0)\}|B\rangle$$

$$j_{\rm em}^\mu = \sum_q Q_q\, \bar q \gamma^\mu q$$

Calculated for low q^2 at **LO in QCD factorization (QCDf)**

Beneke et al '01 and '04

higher powers not fully known ("guesstimated")

↪ recent progress using **analyticity + experimental data on $b \to sc\bar c$** show these corrections should be small

Bobeth et al. '17, Gubernari, et al. '20 and '22

New Physics Fit

$b \to s\ell^+\ell^-$ observables

- $R_K, R_{K^*}, R_{K_S}, R_{K^{*+}}$
- $\mathrm{BR}\left(B_{s,d} \to \mu^+\mu^-\right)$
- $\mathrm{BR}\left(B_s \to e^+e^-\right)$
- $\mathrm{BR}(B \to X_s\, \mu^+\mu^-)$
- $\mathrm{BR}(B \to X_s\, e^+e^-)$
- $\mathrm{BR}(B \to K^* e^+e^-)$: BR, ang. Obs.
- $B_s \to \phi\, \mu^+\mu^-$: BR, ang. obs.
- $B^{0(+)} \to K^{0(+)}\mu^+\mu^-$: BR, ang. obs.
- $B^{(+)} \to K^{*(+)}\mu^+\mu^-$: BR, ang. obs.
- $\Lambda_b \to \Lambda\, \mu^+\mu^-$: BR, ang. obs.

Many observable interconnected via Wilson coefficients ⇒ Global fits

Minimization of χ^2, scanning over the values of δC_i

$$\chi^2 = \left(\vec{O}^{\rm th}(\delta C_i) - \vec{O}^{\rm exp}\right) \cdot \left(\Sigma_{\rm th} + \Sigma_{\rm exp}\right)^{-1} \cdot \left(\vec{O}^{\rm th}(\delta C_i) - \vec{O}^{\rm exp}\right)$$

$\left(\Sigma_{\rm th} + \Sigma_{\rm exp}\right)^{-1}$: the inverse covariance matrix

Theoretical uncertainties and correlations

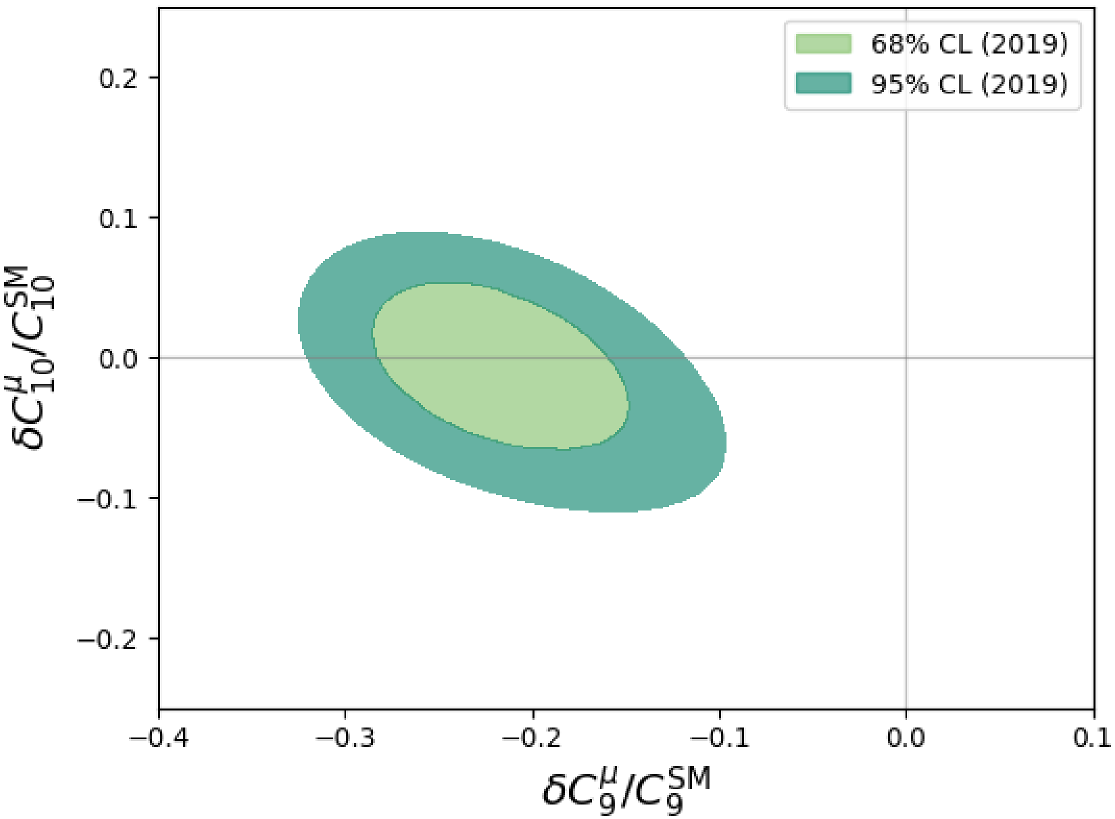
- Monte Carlo analysis
- Variation of the input parameters: masses, scales, CKM, decay constants, form factors, …
- Parameterization of uncertainties due to power corrections:

Leading Order QCDf of non-factorisable piece $\times \left(1 + a_k \exp(i\phi_k) + b_k \frac{q^2}{6\ \mathrm{GeV}^2} \exp(i\theta_k)\right)$ with a_k 10 to 60%, $b_k \sim 2.5 a_k$

Computations performed using **SuperIso** public program

NP fit with two operators; all observables

2-dimensional fit to all available data



2019: Run I results

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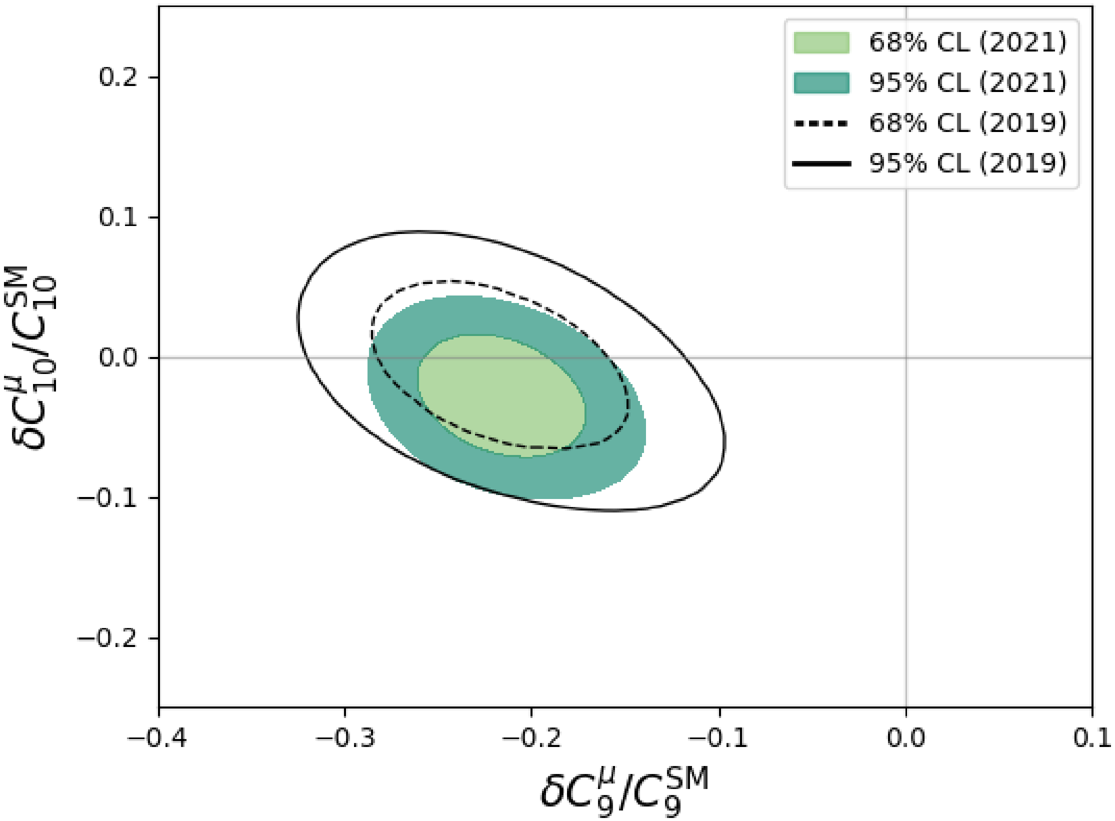

2019: Run I results

2021: (partial) Run II updates, mainly for $B \to K^* \mu^+ \mu^-$, R_K and $B_s \to \mu^+ \mu^-$ (LHCb)

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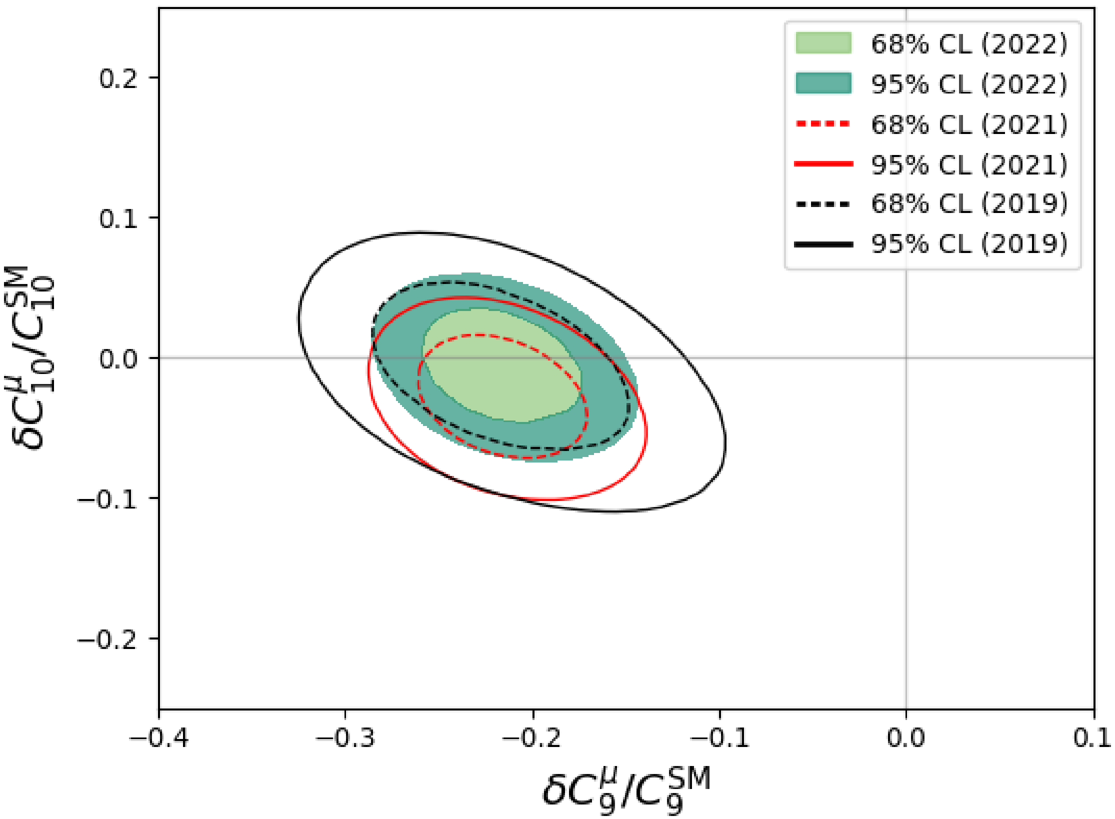

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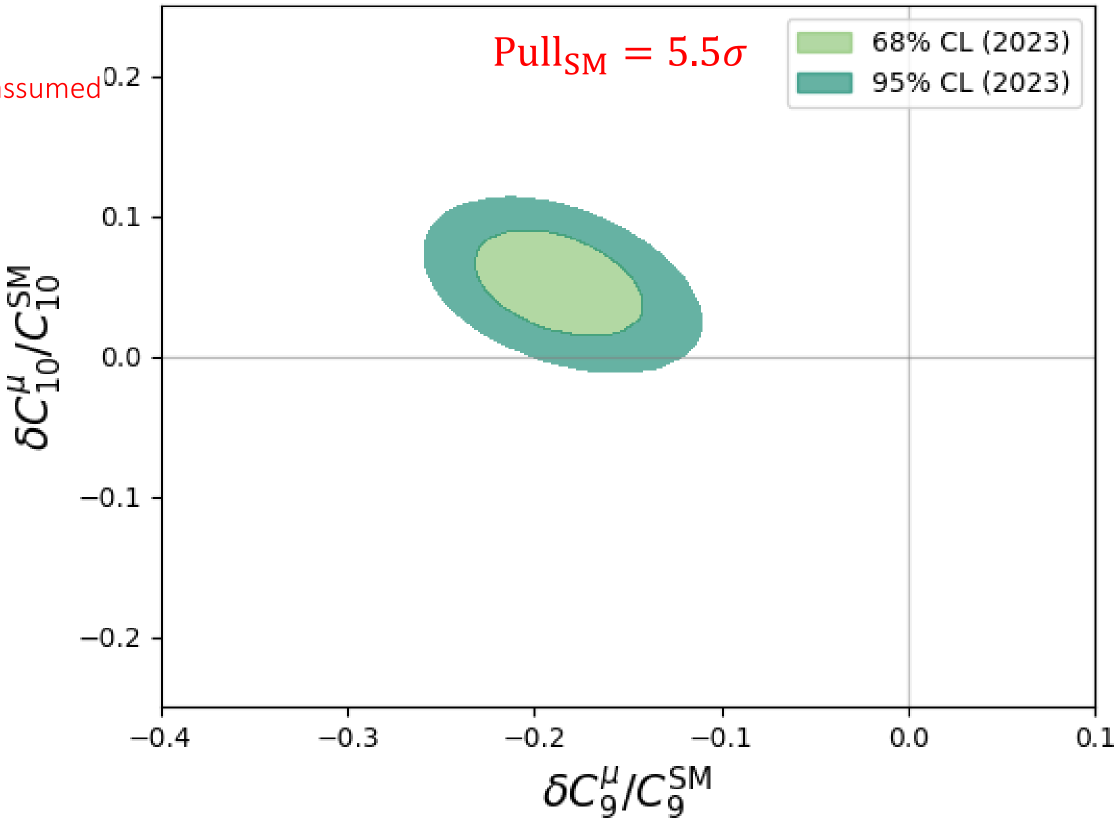
2021: (partial) Run II updates, mainly for $B \to K^* \mu^+ \mu^-$, R_K and $B_s \to \mu^+ \mu^-$ (LHCb)

2022: (partial) Run II updates, mainly for $B_s \to \mu^+ \mu^-$ (CMS), $R_{K^{*+}}$, $R_{K_S^0}$ and $B_s \to \phi \mu^+ \mu^-$

NP fit with two operators; all observables

2-dimensional fit to all available data

NP significance depends on assumed hadronic uncertainties!



Post LHCb $R_{K^{(*)}}$ update - also includes 2023 CMS results on R_K and BR($B^+ \to K^+\mu\mu$)

"*Unnatural*" cancellation between C_9^{μ} and C_{10}^{μ} to compensate the LFUV introduced

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2-dimensional fit to all available data
Impact of separated based on theoretical treatment and uncertainty

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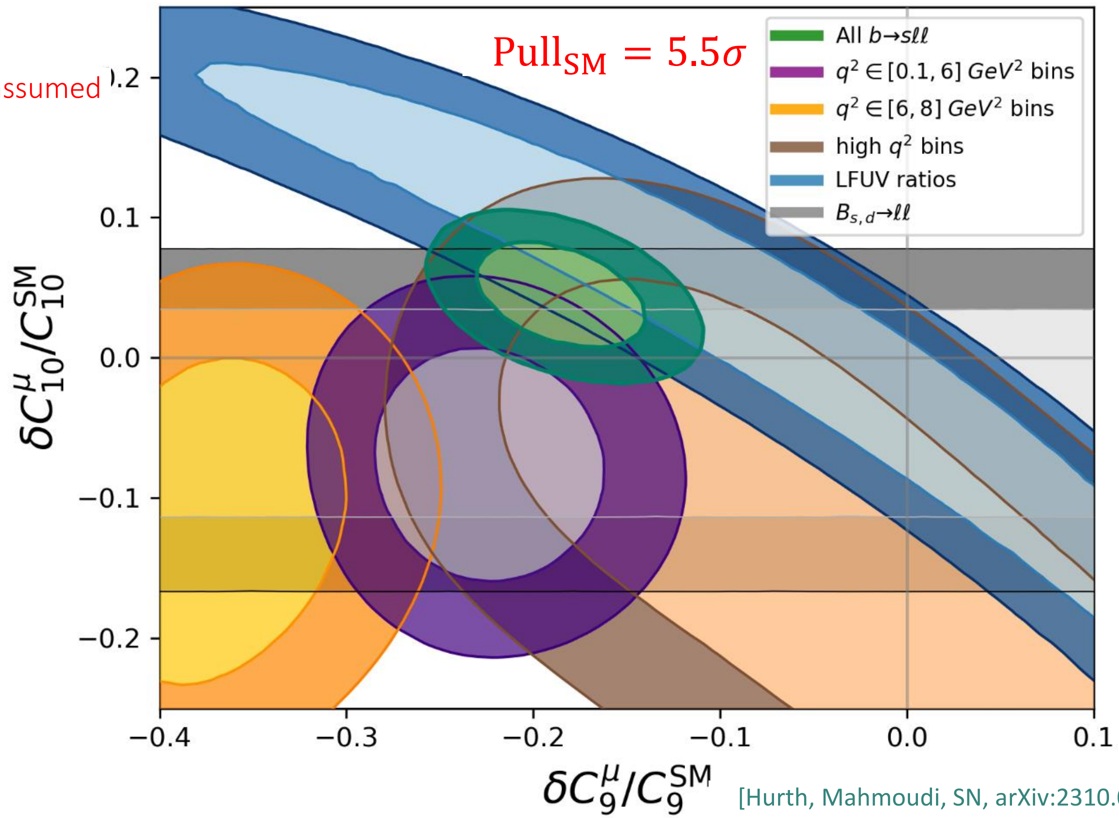

[Hurth, Mahmoudi, SN, arXiv:2310.05585]

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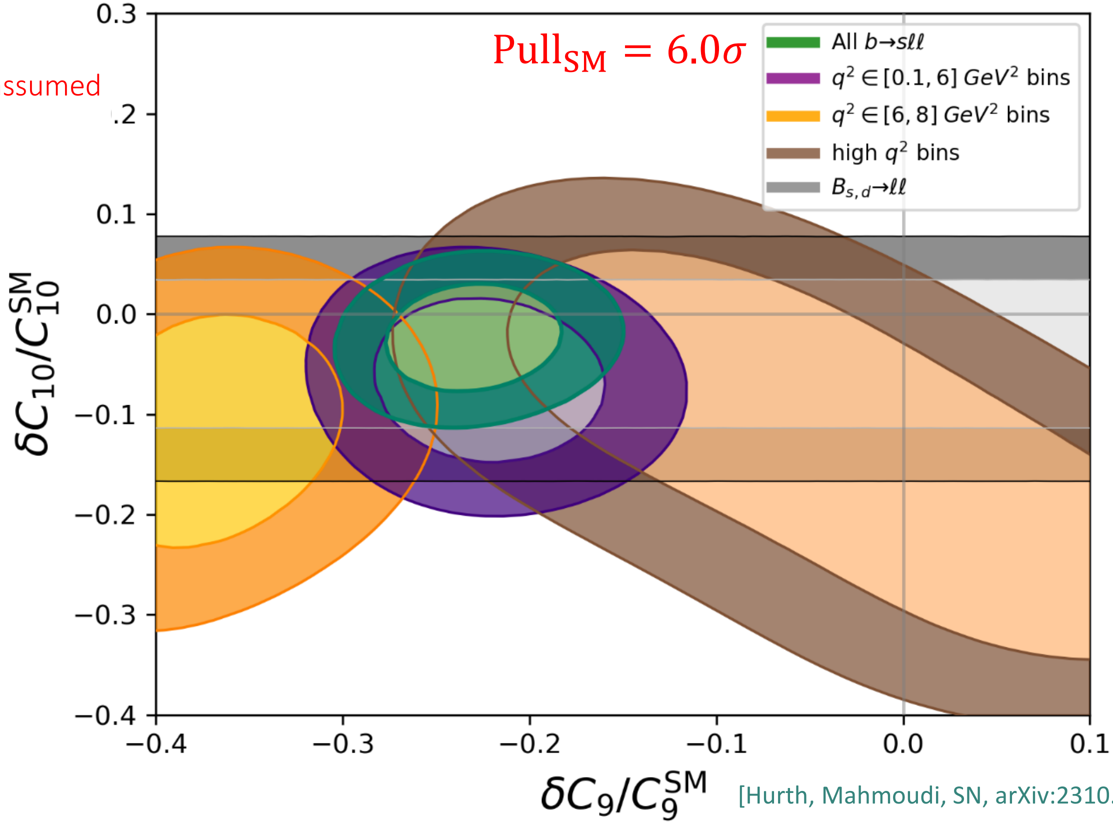

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Rare Kaon decays

Rare kaon decays ($s \to d$ transitions):

- More complicated to gain information on short-distance physics
- Long-distance contributions often dominating
- Most cases, large uncertainties for SM prediction

Weak Effective Theory, similar to $b \to s$:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{td} \frac{\alpha_e}{4\pi} \sum_k C_k^\ell O_k^\ell$$

$$O_9^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu \ell)\,,\;\; O_{10}^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,,\;\; O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\, \gamma^\mu (1-\gamma_5)\, \nu_\ell)$$

NP with rare kaon decays

Rare kaon decays ($s \to d$ transitions):

- More complicated to gain information on short-distance physics
- Long-distance contributions often dominating
- Most cases, large uncertainties for SM prediction

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We assume charged and neutral leptons are related to each other by the $SU(2)_L$ gauge symmetry and we work in the chiral basis:

$$\delta C_L^\ell \equiv \delta C_9^\ell = -\delta C_{10}^\ell$$

Golden channel with precise theory prediction $K \to \pi\nu\bar{\nu}$

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \frac{\kappa_+(1+\Delta_{\mathrm{EM}})}{\lambda^{10}} \frac{1}{3} s_W^4 \sum_\ell \left[\mathrm{Im}^2\Big(\lambda_t C_L^\ell\Big) + \mathrm{Re}^2\Big(-\frac{\lambda_c X_c}{s_W^2} + \lambda_t^{sd} C_L^\ell\Big)\right]$$

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$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})^{\mathrm{SM}} = (7.86 \pm 0.61) \times 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})^{\mathrm{SM}} = (2.68 \pm 0.30) \times 10^{-11}$$

[D'Ambrosio, Iyer, Mahmoudi, SN, JHEP 09 (2022) 148]

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})^{\mathrm{exp}} = (10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$$

[NA62, JHEP 06 (2021) 093]

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[KOTO, PRL 122 (2019) 021802]

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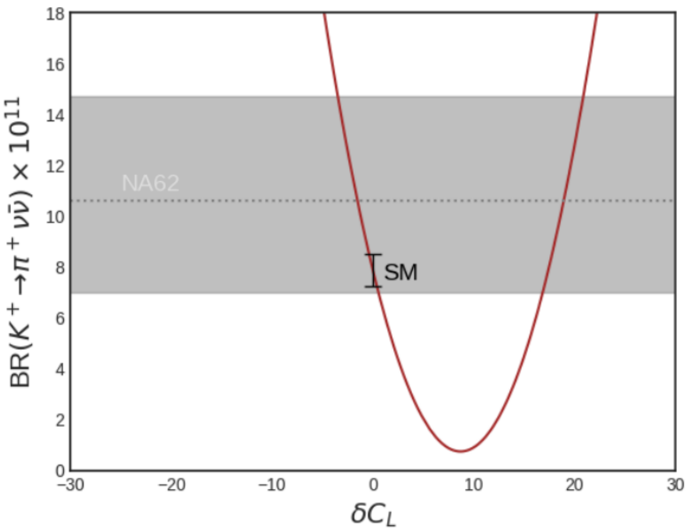

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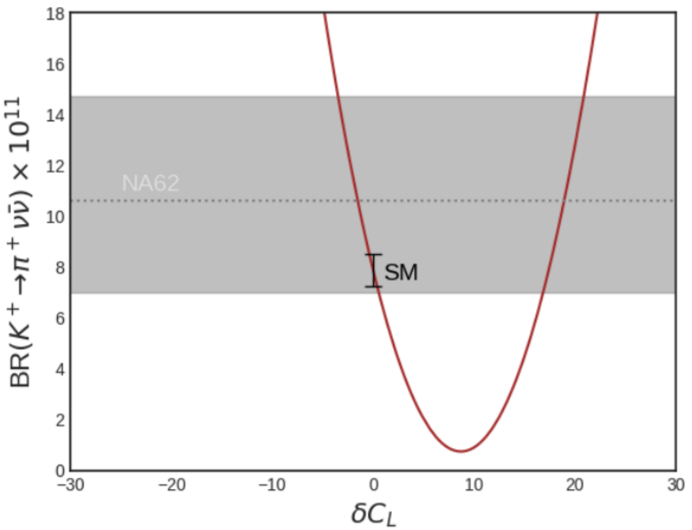

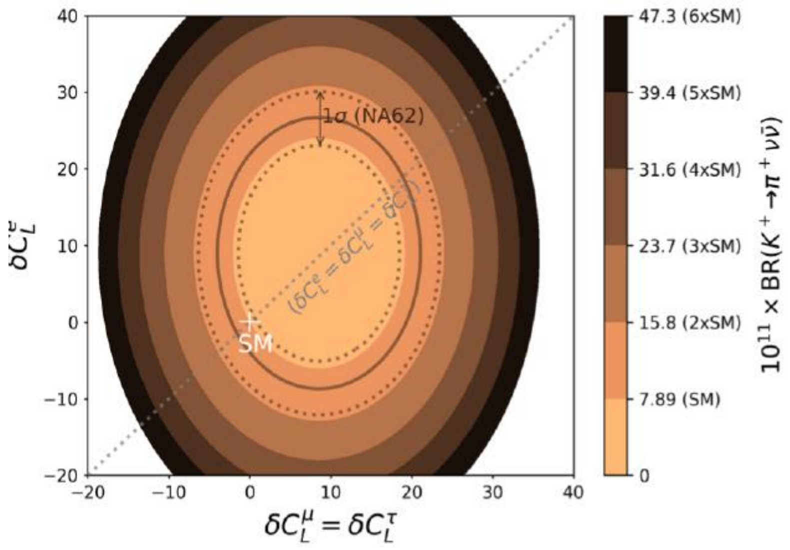

$K^+ \to \pi^+ \ell \bar{\ell}$

$K^+ \to \pi^+ \ell \bar{\ell}$ is long distance dominated, mediated by $K^+ \to \pi^+ \gamma^*$

$$d\Gamma/dz \propto G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$$

$z = m(\ell^+ \ell^-)/M_K^2$

a and b are form factors

$K_{3\pi}$ loop term

- LD effect in a and b are purely universal
- LD contributions cancel out in the difference between $K^+ \to \pi^+ e\bar{e}$ and $K^+ \to \pi^+ \mu\bar{\mu}$

⟹ sensitive only to short-distance effects

$$a_+^{\mu\mu} - a_+^{ee} = -\sqrt{2}\,\mathrm{Re}\left[V_{td} V_{ts}^* (C_9^\mu - C_9^e)\right]$$

Lepton universality predicts the same a, b for $\ell = e, \mu$

Current situation

Channel	a_+	b_+	Reference
ee	-0.561 ± 0.009	-0.694 ± 0.040	comb. [60]
$\mu\mu$	-0.592 ± 0.015	-0.699 ± 0.058	NA62 [16]

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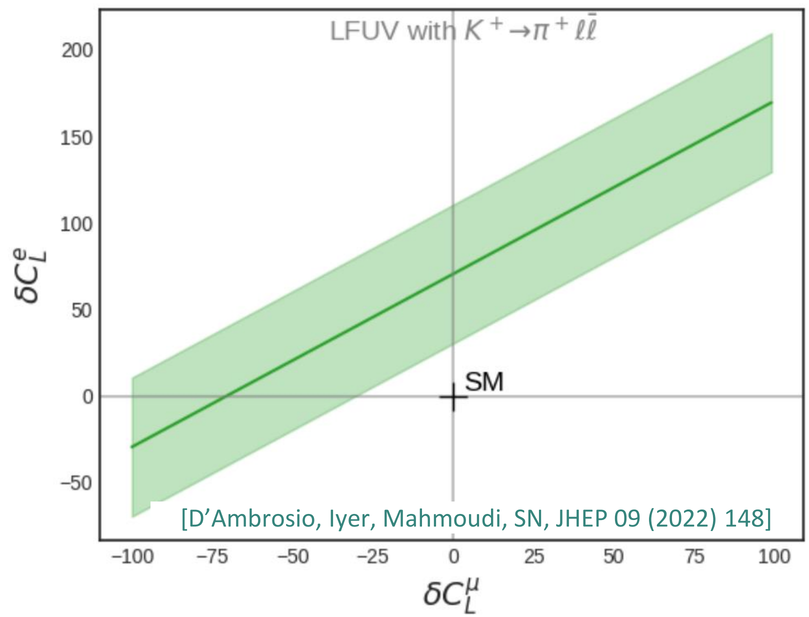
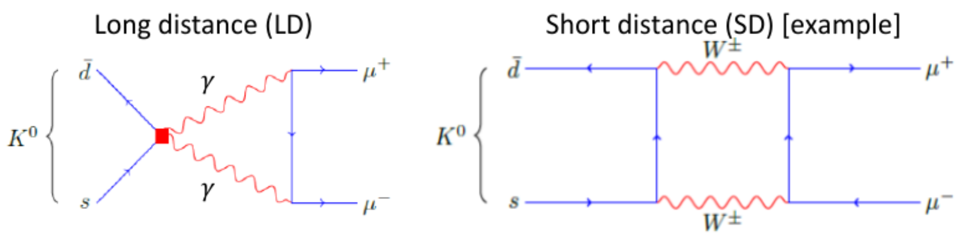


$K_L \to \ell\bar{\ell}$ is long distance dominated, mediated by $K_L \to \gamma^*\gamma^*$

$$\mathrm{BR}(K_L \to \mu\bar{\mu}) = \tau_L \frac{f_K^2 m_K^3 \beta_\mu}{16\pi} \left| N_L^{\mathrm{LD}} - \left(\frac{2m_\mu}{m_K}\frac{G_F\alpha_e}{\sqrt{2}\pi}\right) \mathrm{Re}\left[-\lambda_c \frac{Y_c}{s_W^2} + \lambda_t C_{10}^\ell\right]\right|^2$$

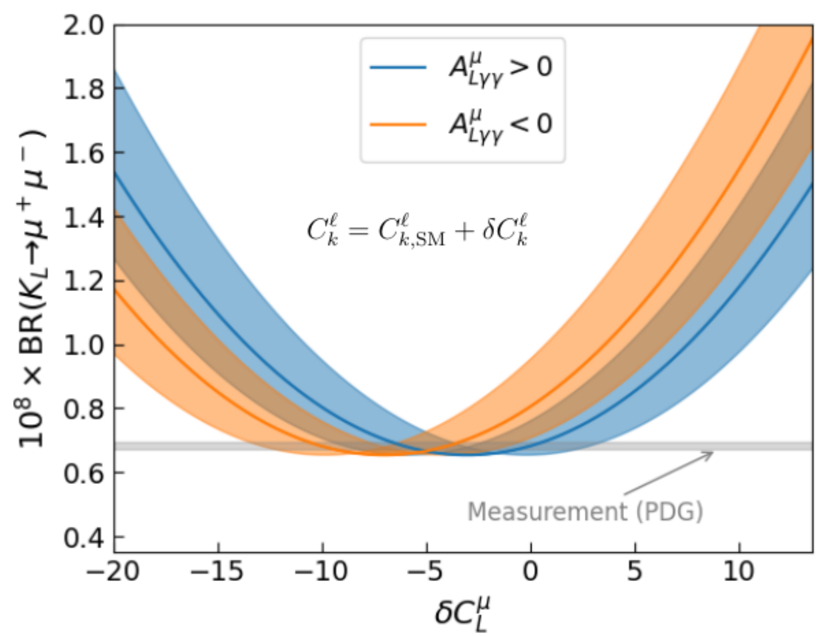
$$N_L^{\mathrm{LD}} = \pm\,[0.54(77) - 3.95i] \times 10^{-11}\,(\mathrm{GeV})^{-2}$$



Prediction depends on the sign of $A(K_L \to \gamma\gamma)$ which determines the effect of the SD-LD interference

$$\mathrm{BR}(K_L \to \mu\bar{\mu})^{\mathrm{SM}} = \begin{cases} \mathrm{LD}(+): & (6.82^{+0.77}_{-0.24} \pm 0.04) \times 10^{-9} \\ \mathrm{LD}(-): & (8.04^{+1.46}_{-0.97} \pm 0.09) \times 10^{-9} \end{cases}$$

[D'Ambrosio, Iyer, Mahmoudi, SN, JHEP 09 (2022) 148]

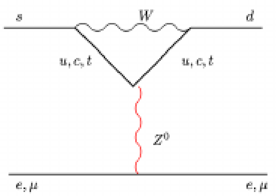


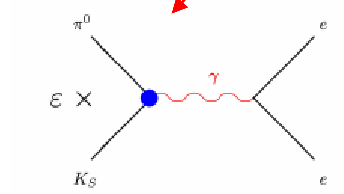
$K_L \to \pi^0 \ell\bar{\ell}$

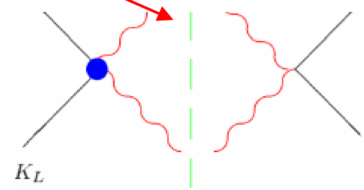
$$\mathrm{BR}(K_L \to \pi^0 \ell\bar{\ell}) = \left(C^\ell_{\rm dir} \pm C^\ell_{\rm int}|a_S| + C^\ell_{\rm mix}|a_S|^2 + C^\ell_{\gamma\gamma}\right)$$

Direct CP-violating

Indirect CP-violating







	$C^\ell_{\rm dir}$	$C^\ell_{\rm int}$	$C^\ell_{\rm mix}$	$C^\ell_{\gamma\gamma}$
$\ell = e$	$(4.62 \pm 0.24)(w_{7V}^2 + w_{7A}^2)$	$(11.3 \pm 0.3)w_{7V}$	14.5 ± 0.5	≈ 0
$\ell = \mu$	$(1.09 \pm 0.05)(w_{7V}^2 + 2.32 w_{7A}^2)$	$(2.63 \pm 0.06)w_{7V}$	3.36 ± 0.20	5.2 ± 1.6

$$w_{7V} = \frac{1}{2\pi}\mathrm{Im}\left[\frac{\lambda_t^{sd}}{1.407\times 10^{-4}}C_9\right], \quad w_{7A} = \frac{1}{2\pi}\mathrm{Im}\left[\frac{\lambda_t^{sd}}{1.407\times 10^{-4}}C_{10}\right]$$

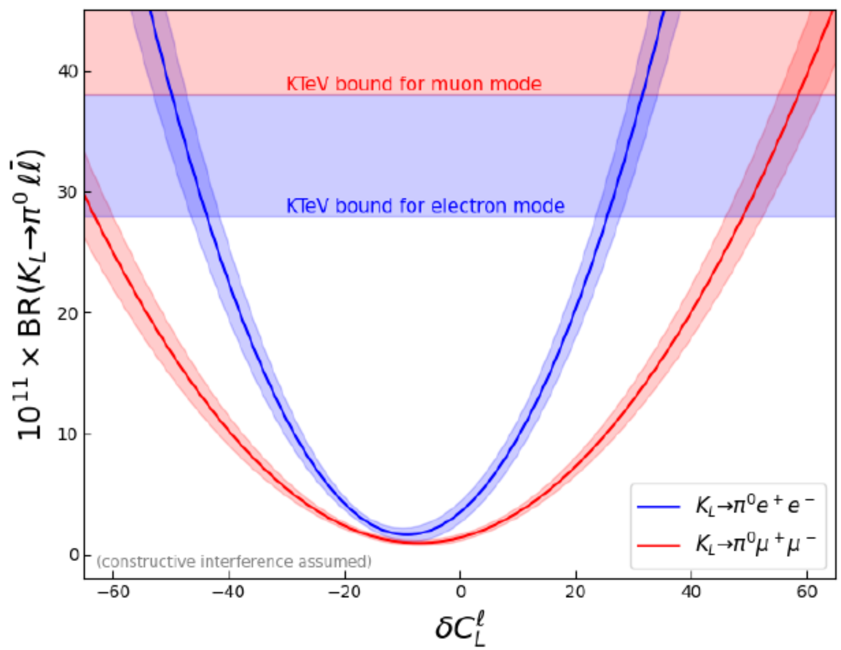
$$\mathrm{BR}^{\rm SM}(K_L \to \pi^0 e\bar{e}) = 3.46^{+0.92}_{-0.80}\,(1.55^{+0.60}_{-0.48}) \times 10^{-11}$$

$$\mathrm{BR}^{\rm SM}(K_L \to \pi^0 \mu\bar{\mu}) = 1.38^{+0.27}_{-0.25}\,(0.94^{+0.21}_{-0.20}) \times 10^{-11}$$

[D'Ambrosio, Iyer, Mahmoudi, SN, JHEP 09 (2022) 148]

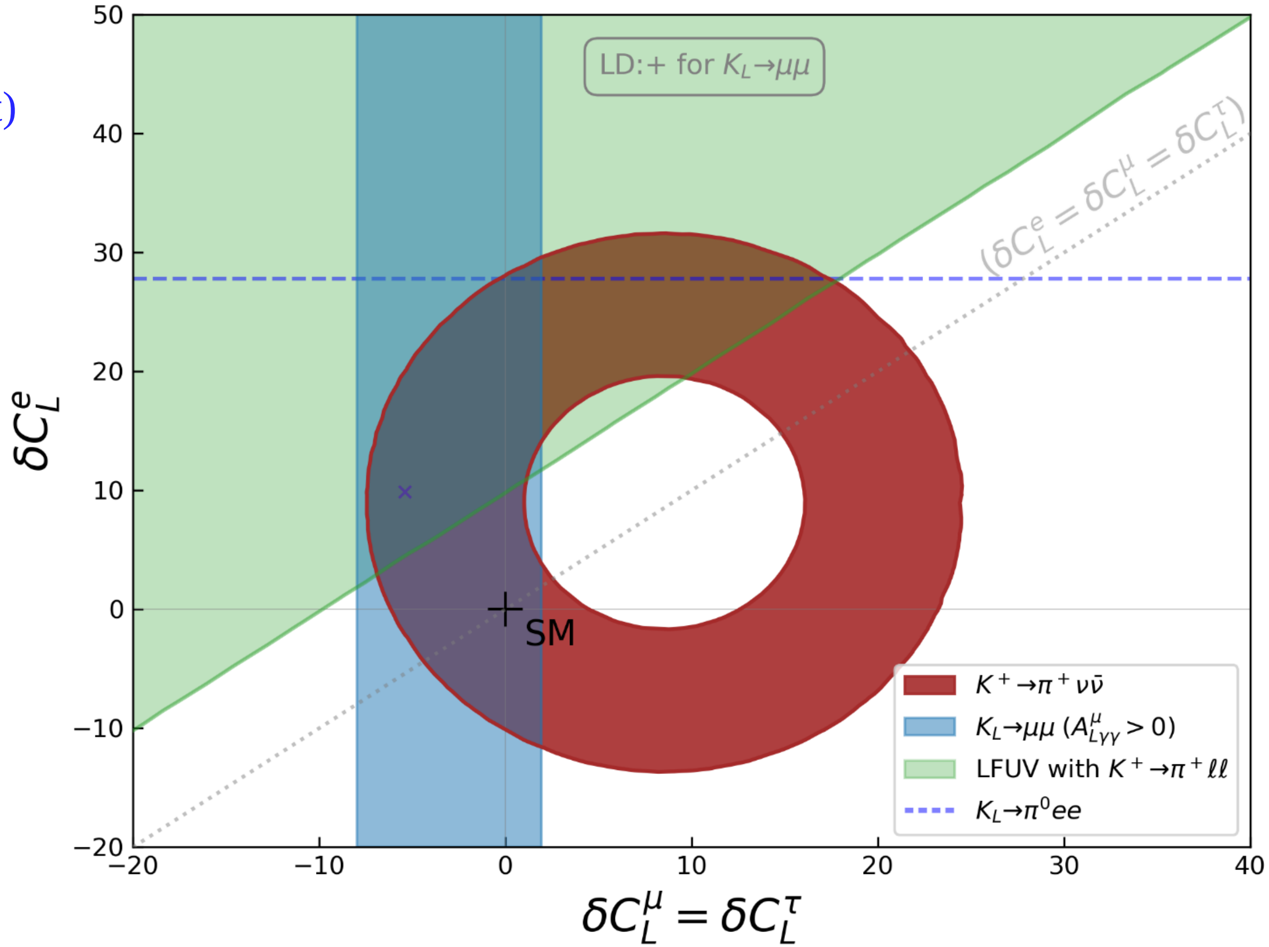
$$\mathrm{BR}^{\rm exp}(K_L \to \pi^0 e\bar{e}) < 28 \times 10^{-11} \quad \text{at } 90\%\ \mathrm{CL}$$

$$\mathrm{BR}^{\rm exp}(K_L \to \pi^0 \mu\bar{\mu}) < 38 \times 10^{-11} \quad \text{at } 90\%\ \mathrm{CL}$$



Current data:

- $K^+ \to \pi^+ \nu\bar{\nu}$
- $K_L \to \mu\bar{\mu}$ (LD:+)
- $K^+ \to \pi^+ \ell\bar{\ell}$
- $K_L \to \pi^0 e\bar{e}$ (90% upper limit)



[D'Ambrosio, Iyer, Mahmoudi, SN, JHEP 09 (2022) 148]

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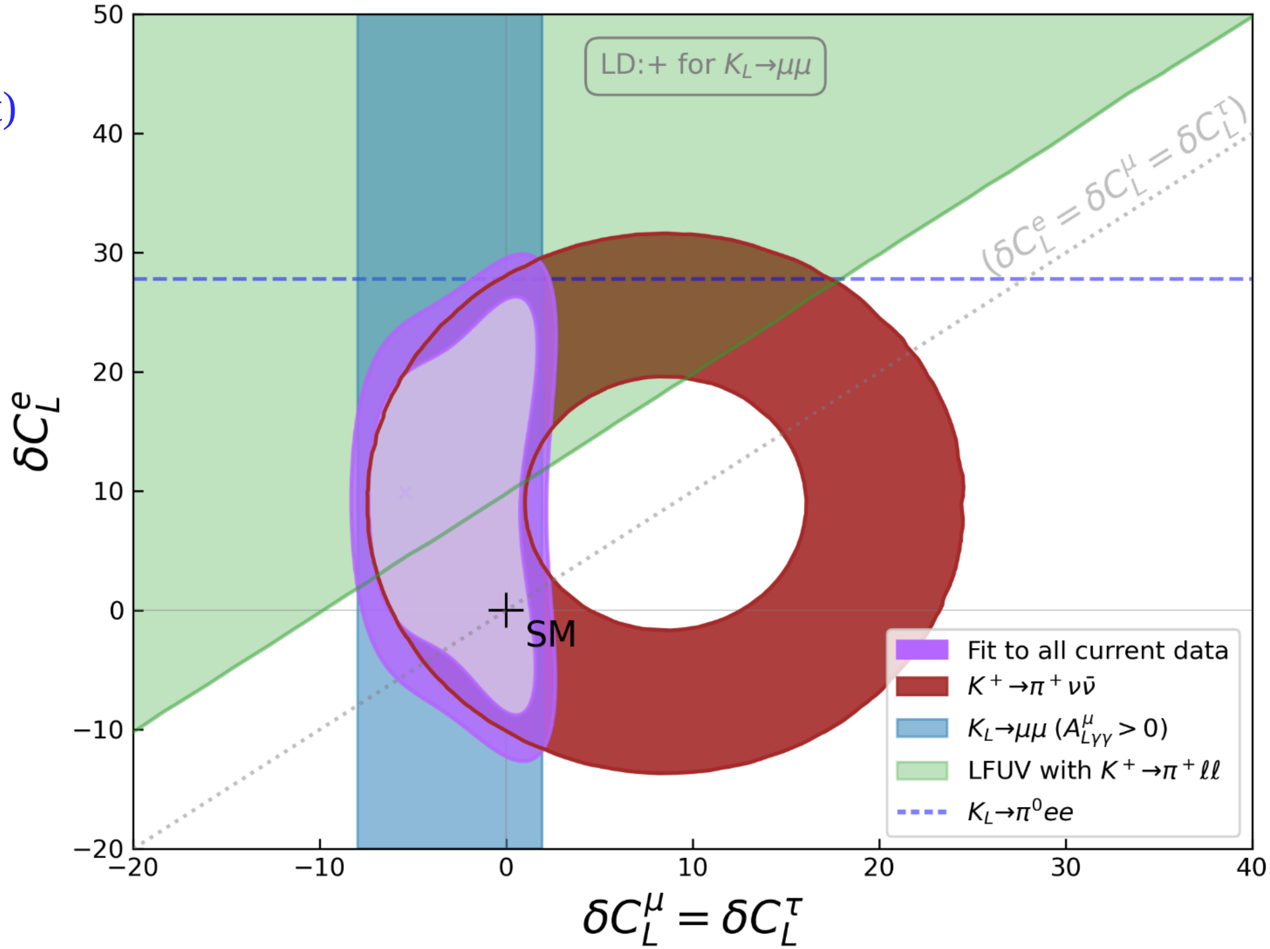
Fit to current data



[D'Ambrosio, Iyer, Mahmoudi, SN, JHEP 09 (2022) 148]

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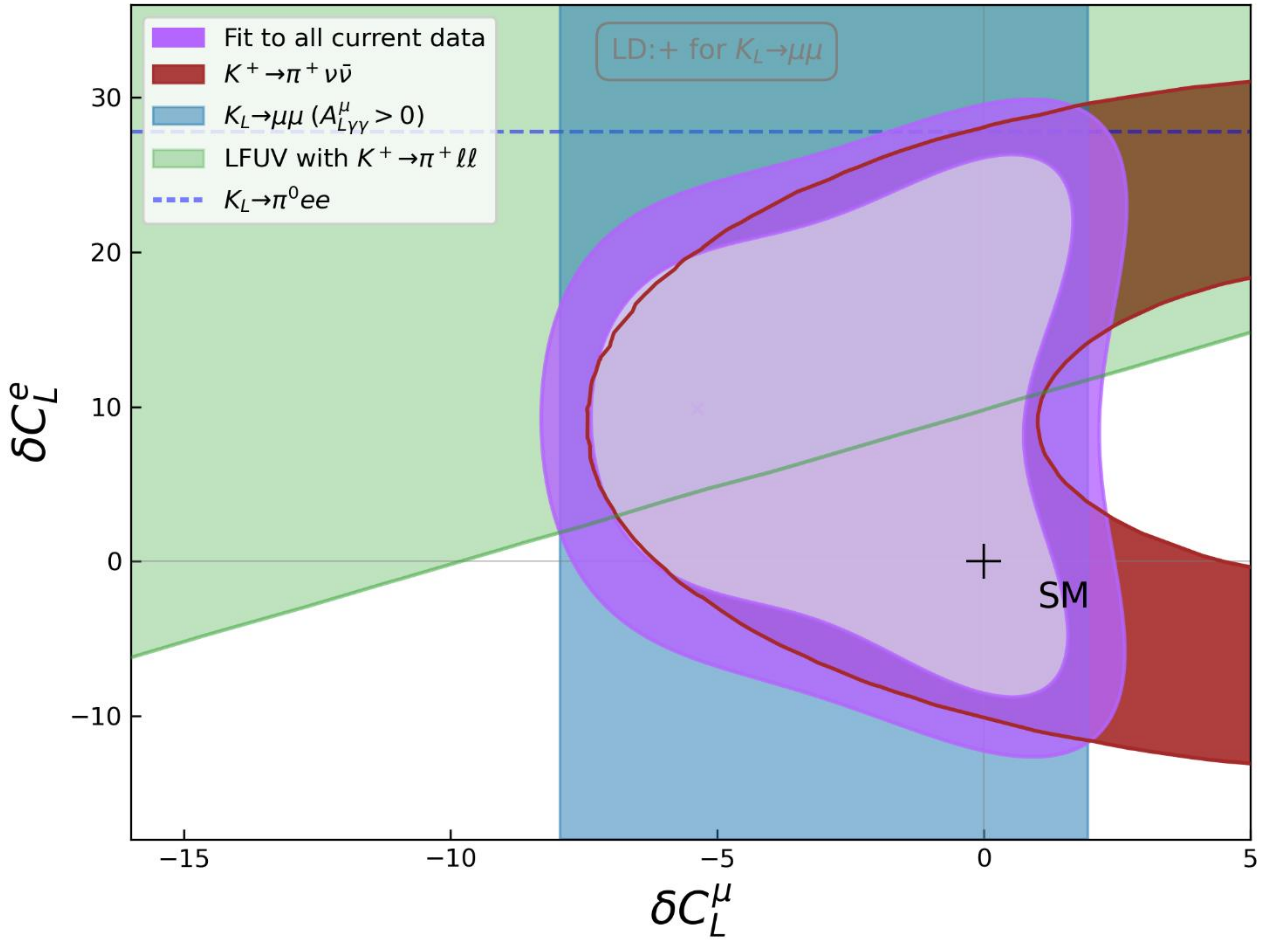

[D'Ambrosio, Iyer, Mahmoudi, SN, JHEP 09 (2022) 148]

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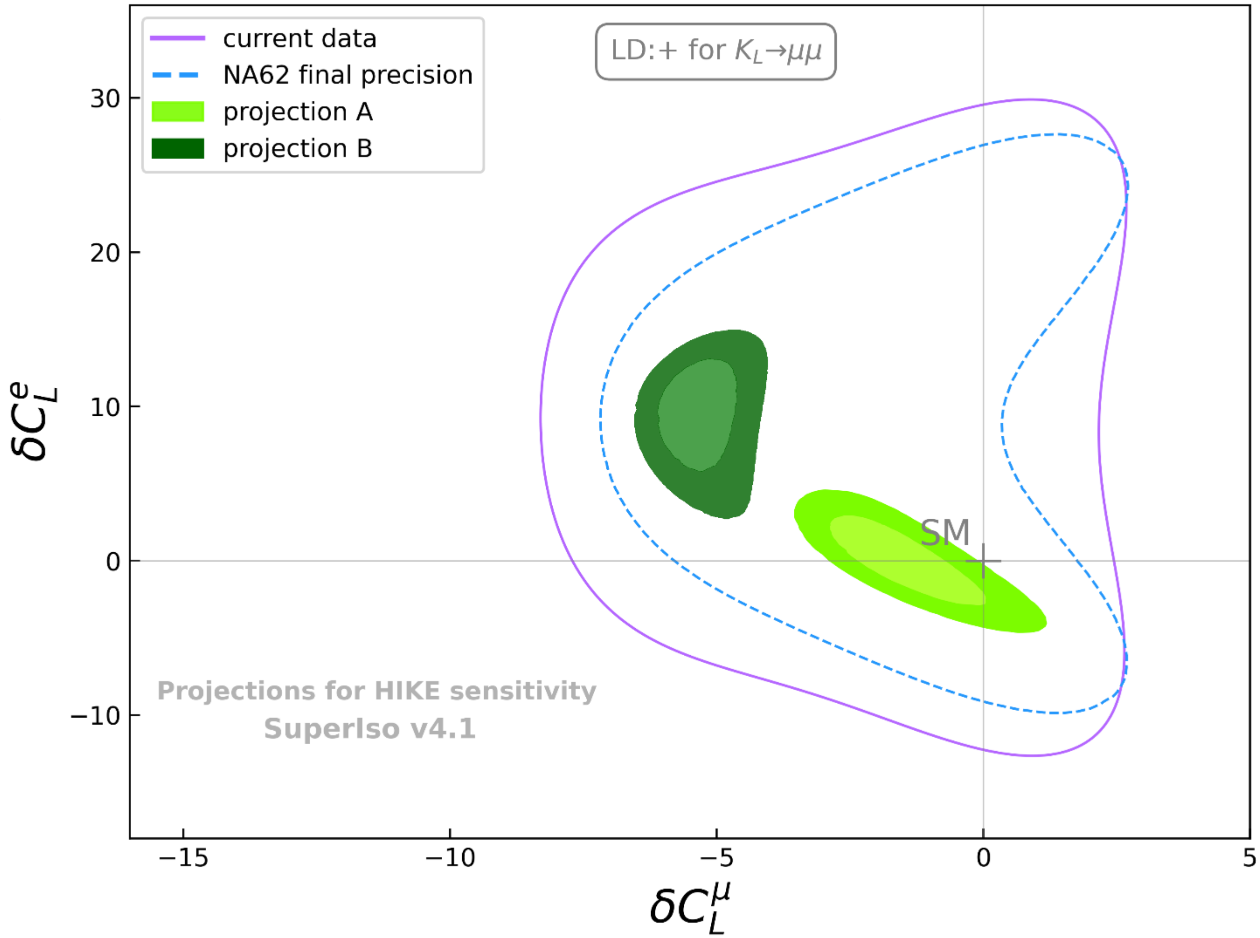

D'Ambrosio, Mahmoudi, SN; work in progress

Future Projections:

Projection A

$K^+ \to \pi^+ \nu\nu$, $K_L \to \mu\mu$, $K^+ \to \pi^+ \ell\ell$ confirmed at target precision of HIKE
$K_L \to \pi^0 ee$ assumes SM value $\pm 20\%$ uncertainty

Projection B

All measurements give current best-fit point used with target precision of HIKE.

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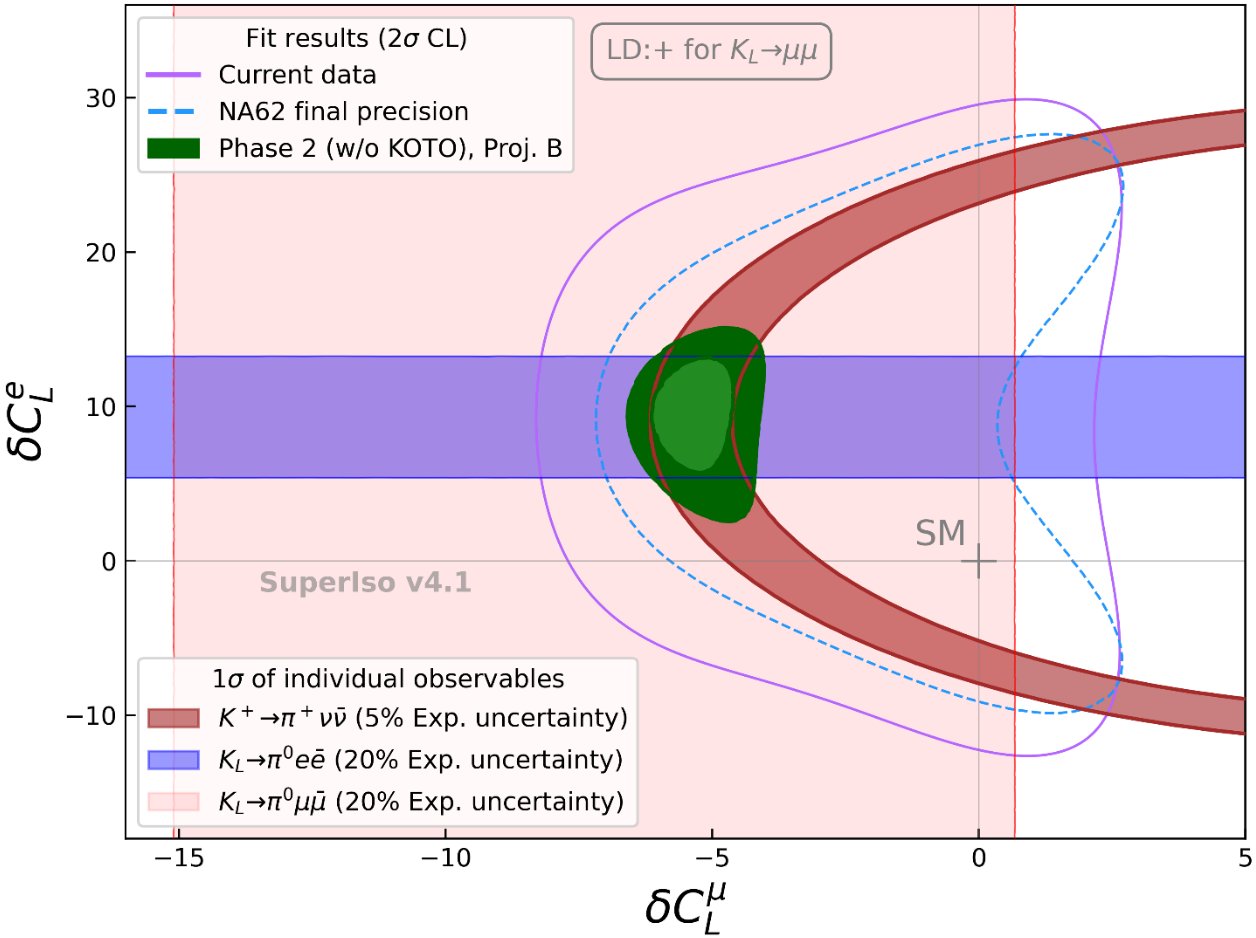

D'Ambrosio, Mahmoudi, SN; work in progress

Conclusions

- Flavour changing neutral current process are effective probes of New Physics
- No sign of LFUV between electrons and muons in $b \to s$ decays but still strong indications of LFU New Physics in $b \to s$ processes mainly as NP contributions to δC_9
- Interesting to see if LHCb in the Run III measures the same anomalies observed in decays to muons, also for electrons (if the anomalies are indeed due to NP, it should!)
- Rare Kaon decays give complementary information on short-distance physics
- Future HIKE data, especially on $K_L \to \pi^0 ee$ will be a very effective (and the only) probe of $s \to d$ transitions for the electron mode

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Thank you!