Quark confinement, Stavanger, 1st August 2022

Round table: $b \to s\ell\ell$ anomalies (theory)

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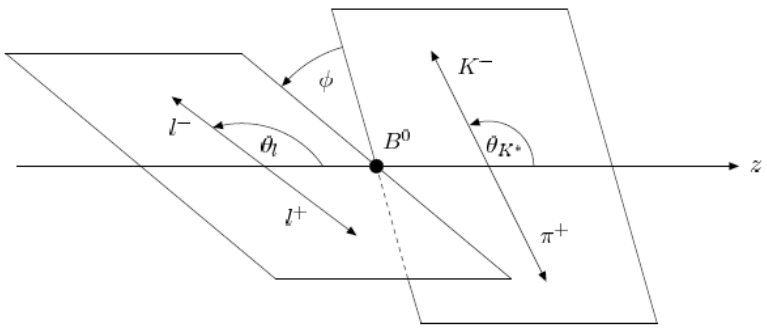
ICREA
The need to know

IFAE

A bit of pre-history....

FCNC $B_d^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$
always played an important role

Parameters: q^2 (dilepton invariant mass), $\theta_l, \theta_{K^*}, \phi$



In 1995 [Ali, Giudice, Mannel] realized that the q_0^2 such that $A_{FB}(q_0^2) = 0$

$$q_0^2 = f(\mathcal{C}_i) \text{ @LO because (s)FF cancel at LO.}$$

Caveat: rather useless and experimentally difficult measure one point in q^2.

Change of paradigm:

- Construct observables that cancel (s)FF at LO for all q^2, [Kruger, JM'05]
- Observables should respect the symmetries of the distribution.

$$A_T^i \to P_i \text{ complete basis full distribution}$$

[J.M. et al.'12, S. Descotes-Genon et al. '13]

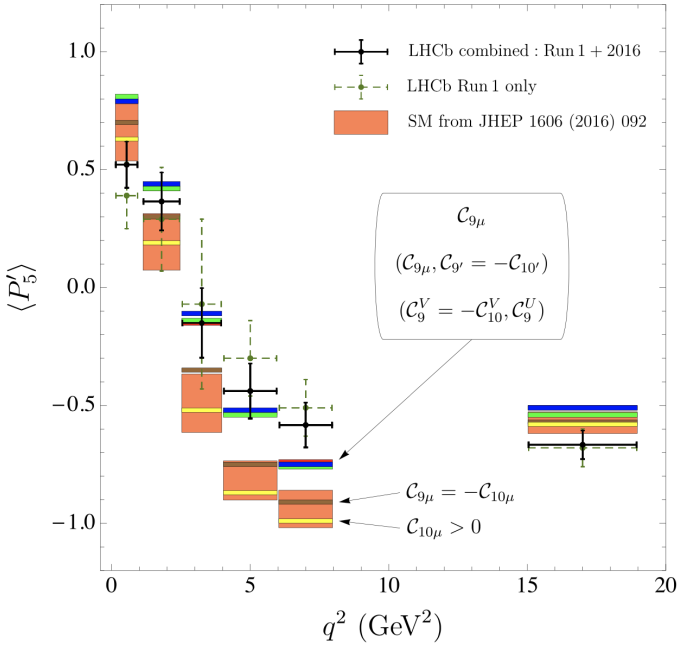
B-Flavour Anomalies

1st anomaly: In 2013 LHCb (N. Serra) announced a large anomaly of 3.7σ in P_5'

Most tested anomaly: LHCb (updated), Belle, ATLAS, CMS.

Also charged channel: $B^+ \to K^{*+}\ell\ell$

... and a large set of BR



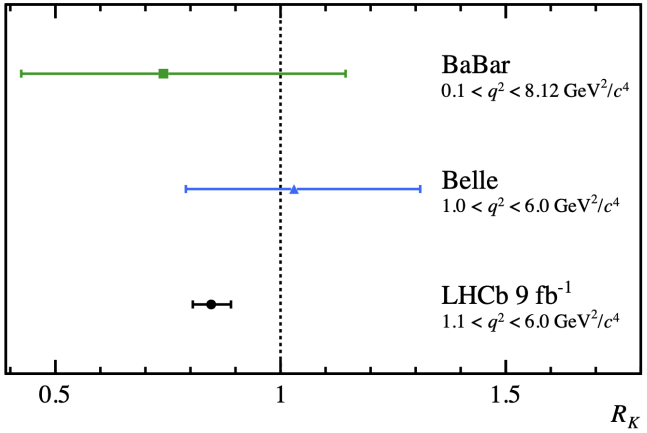
2nd anomaly: Lepton Flavour Universal tests

Measurement of LFU ratio $R_K^{[1.1,6]}$ shows deviation from SM by 3.1σ.

LHCb, arXiv: 2103.11769, Belle, arXiv:1908.01848

$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}$$

Experimental value $R_K^{\rm LHCb} = 0.846^{+0.042+0.013}_{-0.039-0.012}$



... Electrons seem more SM-like than μ.

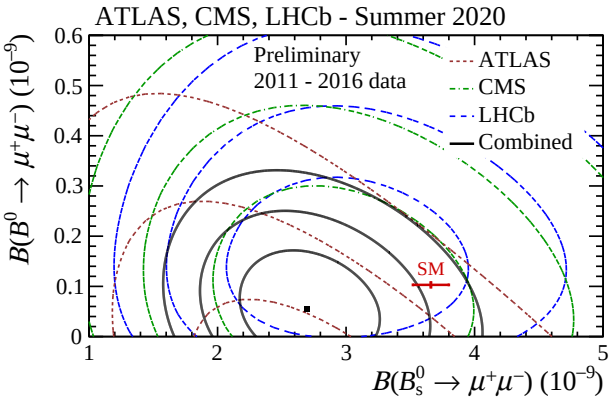
... also R_{K^*} (and charged anomalies by Andrea)

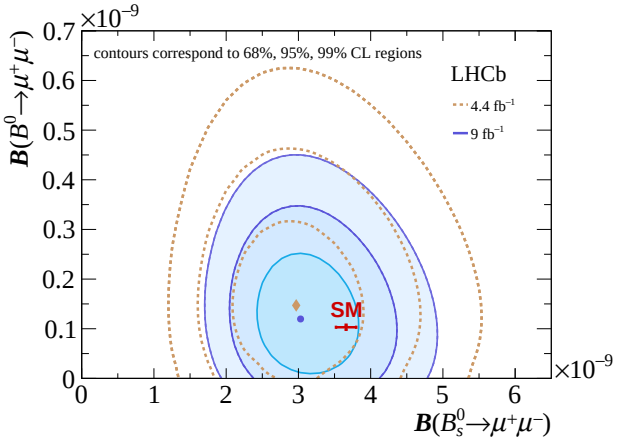
3rd anomaly?: Combination of $B_{s,d} \to \mu^+\mu^-$ measurements

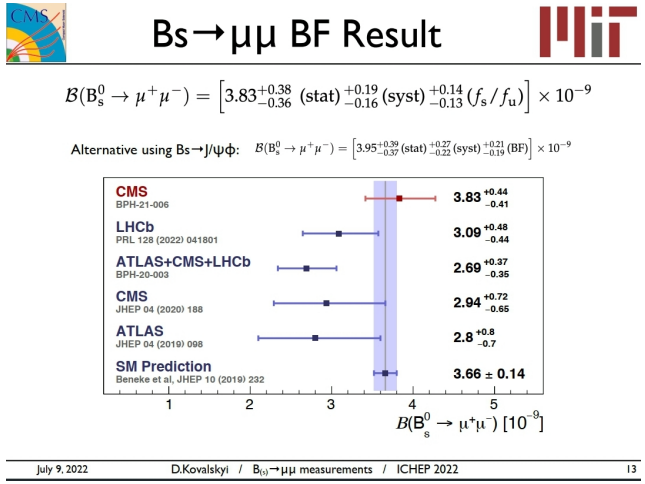
Measurements of BR($B_{s,d} \to \mu^+\mu^-$) by LHCb, CMS, and ATLAS show combined deviation from SM by about 2σ (with LHCb2021).

ATLAS, arXiv:1812.03017
CMS, arXiv:1910.12127
LHCb seminar 23 March 2021

(old combination)







We take instead the average of ATLAS, CMS, LHCb2021 (now closer to SM)

$\mathcal{B}_{B_s \to \mu^+\mu^-} = (2.85^{+0.34}_{-0.31}) \times 10^{-9}$ [Diego Martinez, private communication including rhs LHCb2021]

... waiting patiently for ATLAS update and combination.

Interpretation

- Effective Hamiltonian at scale m_b: $\mathcal{H}_{\text{eff}}^{bs\ell\ell} = \mathcal{H}_{\text{eff, SM}}^{bs\ell\ell} + \mathcal{H}_{\text{eff, NP}}^{bs\ell\ell}$

$$\mathcal{H}_{\text{eff, NP}}^{bs\ell\ell} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i + \text{h.c.}$$

We also include a small λ_u contribution.

- From the set of operators ($\ell = e, \mu$)

$$O_7^{bs} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}\,, \qquad O_7^{\prime bs} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu}\,,$$

$$O_9^{bs\ell\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9^{\prime bs\ell\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{bs\ell\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}^{\prime bs\ell\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

$$\mathcal{C}_i = \mathcal{C}_i^{\text{SM}} + \mathcal{C}_i^{\text{NP}}$$

Wilson coefficient $\mathcal{C}_9^{\text{eff}}$ plays a leading role in understanding the anomalies

[S. Descotes-Genon, JM, J. Virto'13]

Present: Global analyses of $b \to s\ell\ell$ transitions

The latest most complete and updated analysis [M. Algueró et al. EPJC82 (2022) 4, 326]

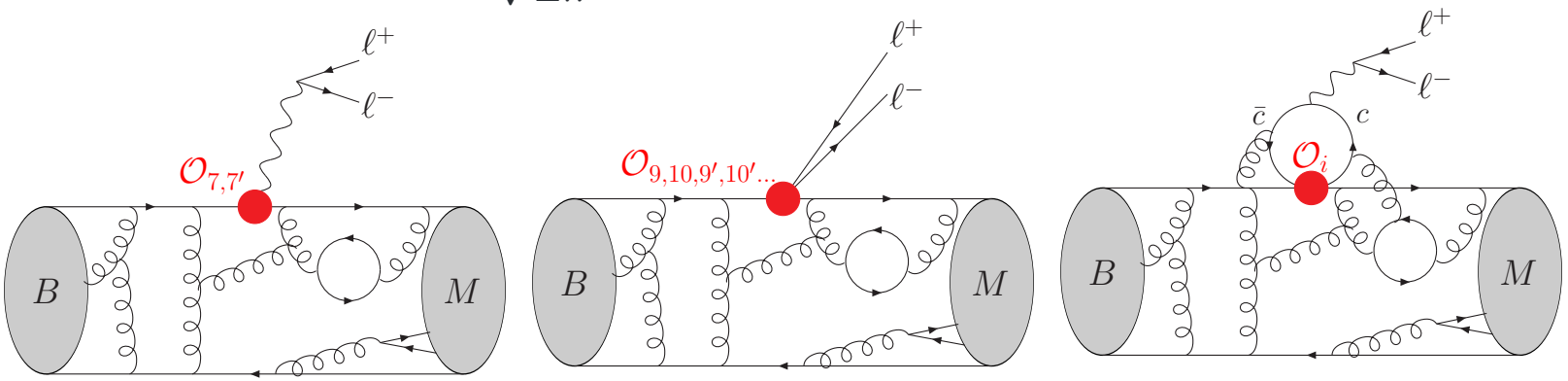
What's in the fits? ⇨ 254 obs (Global) + 24 obs (LFUV) from LHCb, Belle, ATLAS, CMS

- $B^0 \to K^{*0}\mu^+\mu^-$ $(P_{1,2,3}, P'_{4,5,6,8}, F_L)$ LHCb, $(P_1, P'_{4,5,6,8}, F_L)$ ATLAS, P_1, P'_5, F_L CMS
- $B^+ \to K^{*+}\mu^+\mu^-$ $(P_{1,2,3}, P'_{4,5,6,8}, F_L)$ LHCb
- $B^0 \to K^{*0}e^+e^-(P_{1,2}, P_3^{CP}, F_L)$ at low q^2 LHCb
- $B_s \to \phi\mu^+\mu^-$ $(P_1, P'_{4,6}, F_L, BR)$ LHCb
- $BR(B^{+,0} \to K^{+,0}\mu^+\mu^-), BR(B^{+,0} \to K^{*+,0}\mu^+\mu^-)$ LHCb + CMS + Belle
- $BR(B \to X_s\gamma)$ combination CLEO, Belle, Babar
- $BR(B \to X_s\mu^+\mu^-), BR(B \to X_s e^+e^-)$ Babar
- $BR(B_s \to \mu^+\mu^-)$ Average LHCb, ATLAS, CMS
- $B^+ \to K^+\mu^+\mu^-(F_H, A_{FB}), B^+ \to K^{*+}\mu^+\mu^-(F_L, A_{FB})$ CMS
- **LFUV:** $R_{K^{*0}}, R_{K^+}, R_{K^{*+}}, R_{K_S}$ LHCb + Belle
- $P_4'^{\mu,e}, P_5'^{\mu,e}$ (and in combination **LFUV:** $Q_{4,5} = P_{4,5}'^{\mu} - P_{4,5}'^{e}$) Belle
- Radiative decays: $B^0 \to K^{*0}\gamma$ (A_I and $S_{K^*\gamma}$), $B^+ \to K^{*+}\gamma$, $B_s \to \phi\gamma$ PDG

Largest **tensions** with SM in some low-q^2 bins of $P_5'^{\mu}$, in R_K, R_{K^*} and some bins of $BR(B_s \to \phi\mu\mu)$

Two sources of hadronic uncertainties for exclusive

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



Form factors (local) Charm loop (non-local)

- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): form factors

$$A_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle M|\bar{s}\sigma_{\mu\nu} P_R b|B\rangle + \mathcal{C}_9 \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

$$B_\mu = \mathcal{C}_{10} \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

B-meson (or light-meson) DA LCSR + lattice + EFT for correlations

- Non-local contributions (charm loops): hadronic contribs.

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

Charm-loop corrections: Perturbative contribution + magnitude of long-distance contribution (one soft-gluon exchange) inspired by

[Khodjamirian, Mannel, Pivovarov, Wang]

1D Scenarios for $\mathcal{C}_{i\mu}$

Updated results in: M. Algueró et al. EPJC 82 (2022)

	All			LFUV		
1D Hyp.	Best fit	$1\,\sigma$	Pull_{SM}	p-value	$1\,\sigma$	Pull_{SM}
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.01	$[-1.15, -0.87]$	**7.0**	24.0 %	$[-1.11, -0.65]$	**4.4**
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.45	$[-0.52, -0.37]$	**6.5**	16.9 %	$[-0.48, -0.31]$	**5.0**
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}$	-0.92	$[-1.07, -0.75]$	5.7	8.2 %	$[-2.10, -0.98]$	3.2

- *p*-value of SM hypothesis is now 0.44% (2022) for the fit "All"
  and 0.91% (2022) for the fit "LFUV"
- Tension between All fit preference by $C_{9\mu}$ and LFUV-fit by $C_{9\mu} = -C_{10\mu}$.

Same hierarchy of main scenarios was found by other groups, for instance: Hurth, Mahmoudi, Neshatpour, arXiv:2012.12207

What the most relevant observables tell us?

1. $\mathcal{B}_{B_s\to\mu^+\mu^-}$ exhibits a small (but persistent) deviation from the SM.
   $\to \mathcal{C}_{10\mu}^{\text{NP}}$ positive (**small**) or $\mathcal{C}_{10'\mu}^{\text{NP}}$ negative or both or a scalar contribution.

2. P_5' requires a **large** (absolute value) negative contribution to $\mathcal{C}_{9\mu}^{\text{NP}}$

3. R_X signals the **presence of LFUV** and
   it admits many solutions with $C_{9\mu}$ and $C_{10\mu}$ that gives similar results.

Solution: LFU New Physics

[Algueró, Capdevila, Descotes-Genon, Masjuan, JM, PRD'19, 1809.08447]

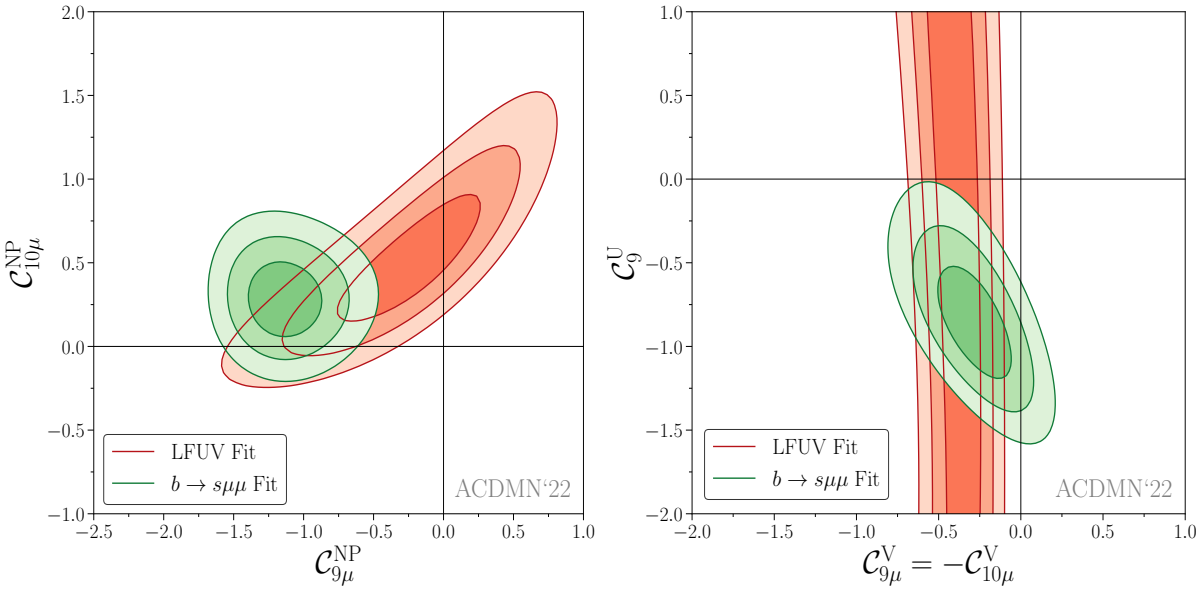
It was proposed: ... to remove hypothesis that NP is purely LFUV

$$\begin{aligned} C_{ie}^{\rm NP} &= C_i^{\rm U} \\ C_{i\mu}^{\rm NP} &= C_{i\mu}^{\rm V} + C_i^{\rm U} \end{aligned}$$

- Common New Physics contribution $C_i^{\rm U}$ to charged leptons.
- Allow to accommodate that LFUV-NP prefers $SU(2)_L$ and LFU-NP is vectorial.

$[C_{9\mu}, C_{10\mu}]$

TENSION between LFUV fit and $b \to s\mu\mu$ fit.



Scn-U:
$[C_{9\mu}^V = -C_{10\mu}^V, C_9^U]$

PERFECT agreement between both fits if LFU allowed.

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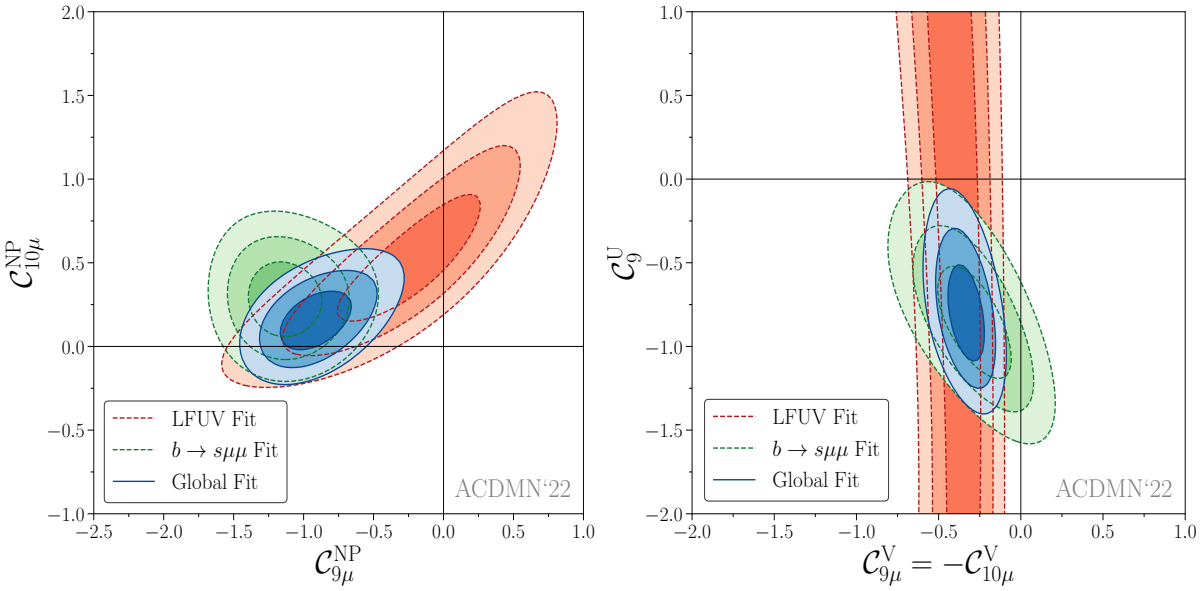

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PERFECT agreement between both fits if LFU allowed.

SMEFT connection between $b \to s\mu\mu$ & $b \to c\ell\nu$ in Scn-U

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$$

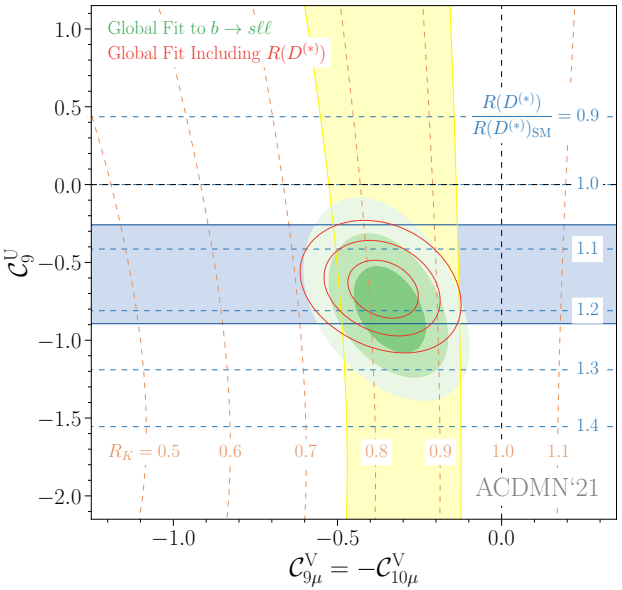
- Two operators with left-handed doublets

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

- FCCC part of $\mathcal{O}^{(3)}_{2333} \Rightarrow R_{D^{(*)}}$
- FCNC part of $\mathcal{O}^{(1,3)}_{2333}$ with $C^{(1)}_{2333} = C^{(3)}_{2333}$

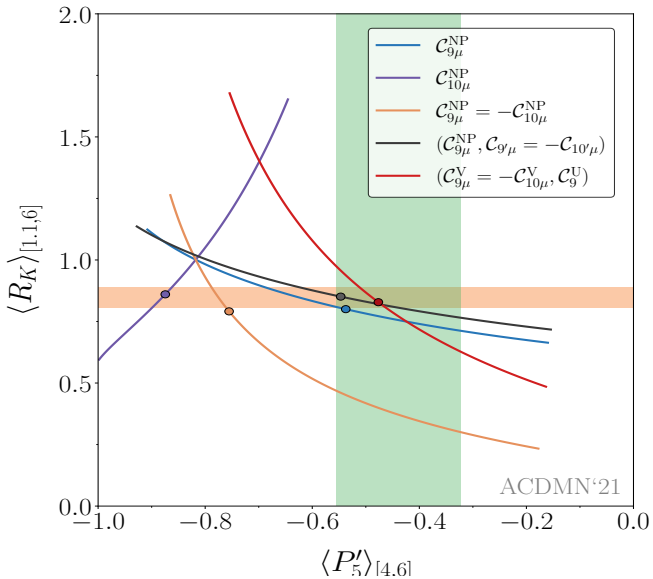
[Capdevila, Crivellin, Descotes, Hofer, JM, PRL 2018]

  - Avoids bounds from $B \to K^{(*)}\nu\nu$
  - Huge enhancement of $b \to s\tau\tau$
  - Through radiative effects: NP $\mathcal{C}_9^{\rm U}$ with $\text{Pull}_{\rm SM} = 8.0\sigma$



Preferred scenarios and consistency with: $\langle P_5' \rangle_{[4,6]}$ vs $\langle R_K \rangle_{[1.1,6]}$

2D Hyp.	Best fit	$\text{Pull}_{\rm SM}$	p-value
Scn-R $(\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$	(-1.15,+0.17)	7.1	31.1 %
Scn-U $(\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}, \mathcal{C}_9^{U})$	(-0.34,-0.82)	7.2	34.5 %



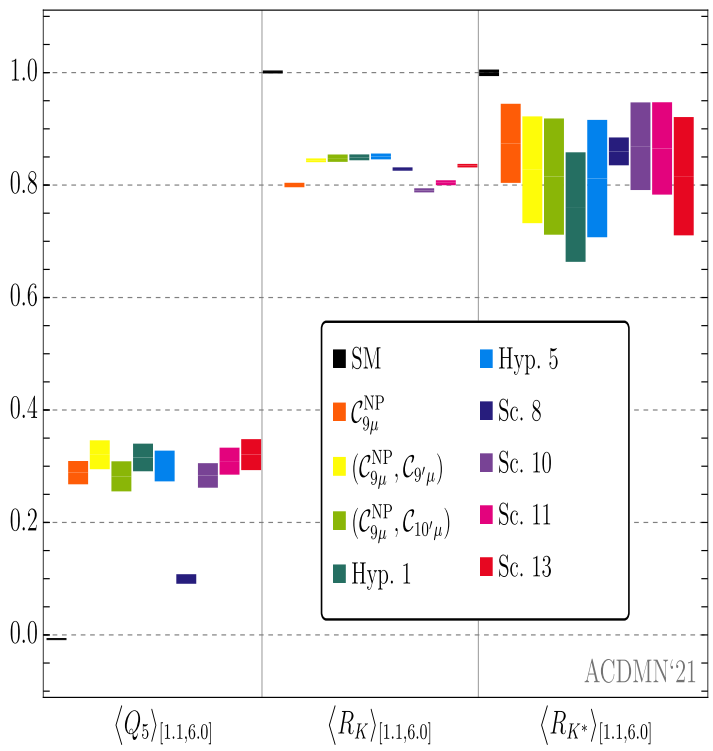
Future: $\mathcal{C}_{9\mu}^{\rm NP}$ is the leading New Physics coefficient

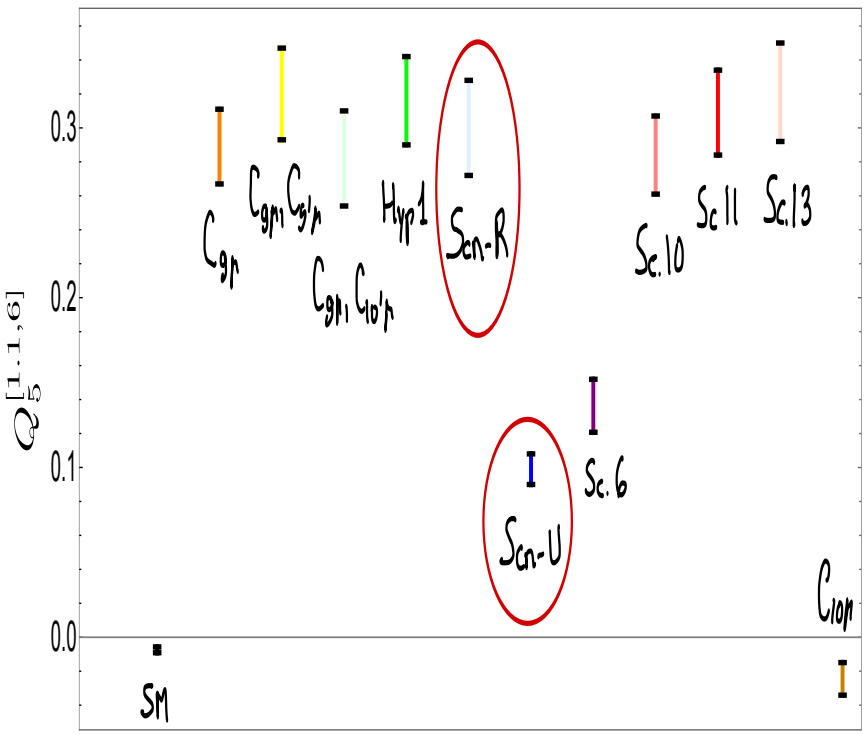
$$\mathcal{C}_{9\mu}^{\rm eff} \to \mathcal{C}_{9\mu\, j}^{\rm eff} = \mathcal{C}_{9\mu\,{\rm pert}}^{\rm SM} + \mathcal{C}_{9\mu}^{\rm NP} + \mathcal{C}_{9\mu\, j}^{c\bar{c}\, B\to K^*} \qquad \mathcal{C}_{9\mu}^{\rm NP} = \mathcal{C}_{9\mu}^{\rm V} + \mathcal{C}_{9}^{\rm U}$$

Two main inputs required from experiment (**urgently**):

[M. Alguero, B. Capdevila, JM, AC, PRD 105 (2022) 11]

- An LFUV $\mathcal{C}_{9\mu}^{\rm V}$ dominated observable: $\mathbf{Q_5} = \mathbf{P_5'^{\mu}} - \mathbf{P_5'^{e}}$
- $\mathbf{b} \to \mathbf{s}\tau\tau$ governed processes may be linked to $\mathcal{C}_{9}^{\rm U}$.





Possible solutions...

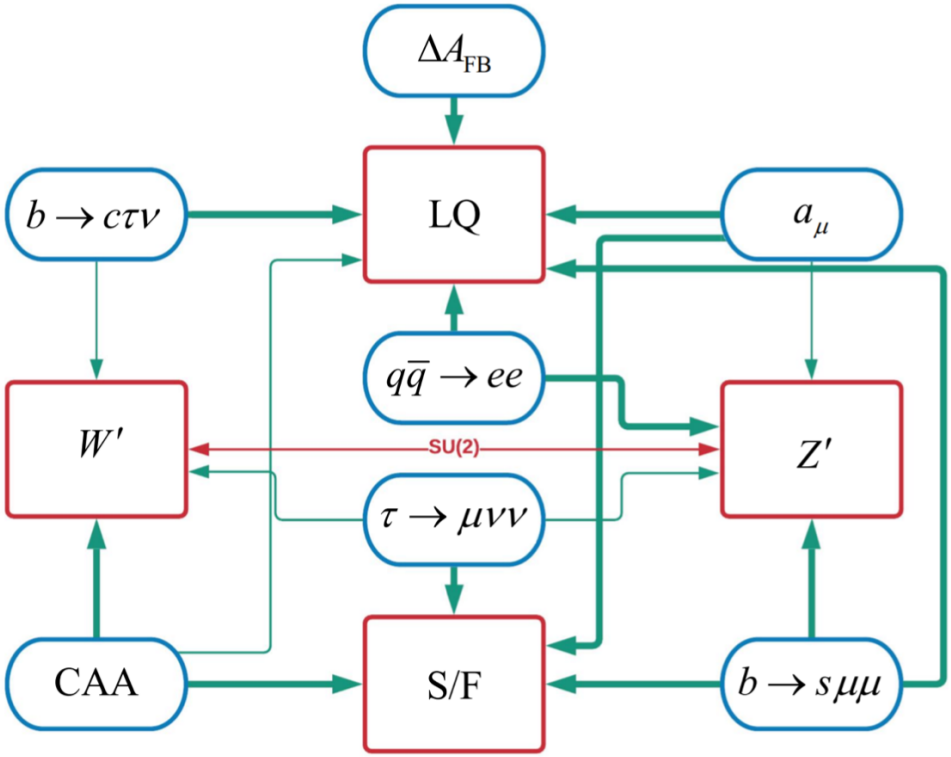


Figure 1. Synthesis of possible explanations (red boxes) of the anomalies (blue boxes). The arrows indicate to which extensions of the SM the anomalies point. Thick arrows stand for probable explanations without significant experimental or theoretical shortcomings while the thin ones indicate that the new particles can only partially explain the measurement or generate problems in other observables. The red arrow indicates that the Z' and W' could be components of a single $SU(2)_L$ triplet.

LFU-NP: Tau loops

Four-fermion operators of the type $\bar{s}\gamma^\mu P_L b \bar{\tau}\gamma_\mu \tau$

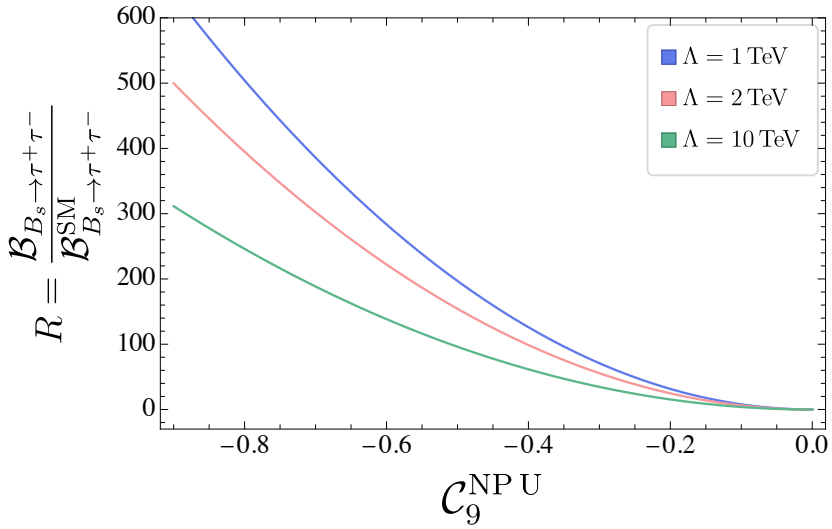
$$\Rightarrow \mathcal{C}_9^{\rm NPU} \propto \mathcal{C}_9^{\tau\tau}$$

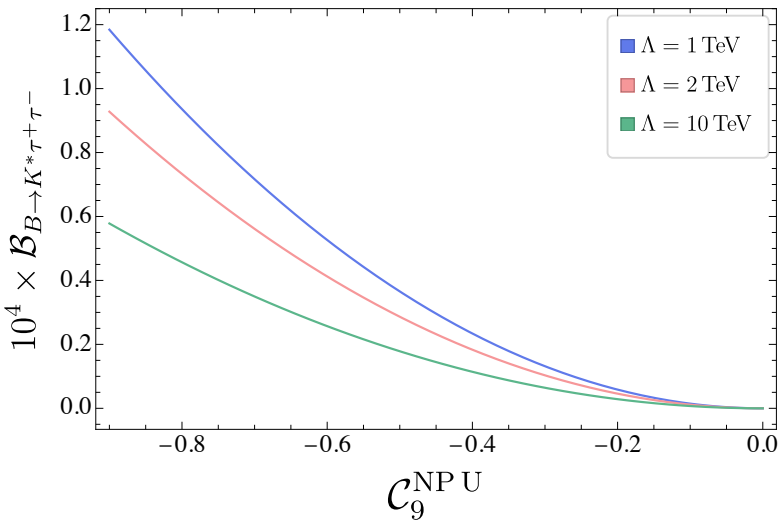
via off-shell γ penguin with $O_9^{\tau\tau}$

IF assumed that LQs is the most plausible solution also $C_{10}^{\tau\tau}$ is present

- $\mathcal{C}_9^{\tau\tau} = \mathcal{C}_{10}^{\tau\tau}$ in case of S_2 LQ
- $\mathcal{C}_9^{\tau\tau} = -\mathcal{C}_{10}^{\tau\tau}$ in case of U_1 or $S_1 + S_3$ LQs

A measurement of $\mathcal{B}_{B_s\to\tau^+\tau^-}$ and/or $\mathcal{B}_{B\to K^{(*)}\tau^+\tau^-}$ will give us information on $\mathcal{C}_9^{\rm NP\,U}$





In summary....

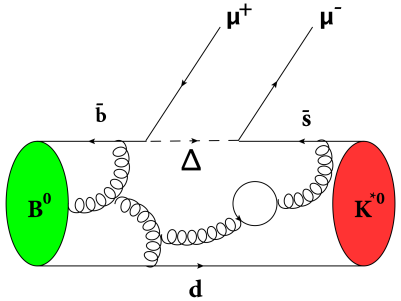
...our search for New Physics

BACK-UP slides

A possible successful candidate?

A very promising candidate is:

Vector leptoquark SU(2) singlet:
$U_1(3,1,2/3)$
Coupled mainly to 3rd generation

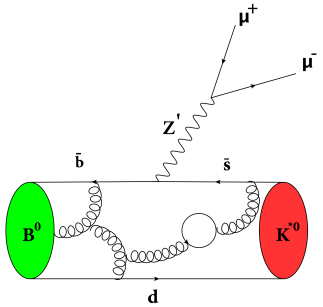


- It can explain both charged and neutral anomalies
- $C_9^V = -C_{10}^V$ pattern
- No tree level effect for $b \to s\nu\bar{\nu}$
- No conflict with direct searches

Good solution, but challenging UV completion.

Examples: $SU(4) \times U(2)_L \times SU(2)_R$+vector like ferm (Calibbi, Crivellin, Li), $SU(4) \times U(2) \times SU(2)_R$ in RS (Blanke, Crivellin),...

Many realizations of LFUV Z' models (if only $b \to s\ell\ell$ is considered).

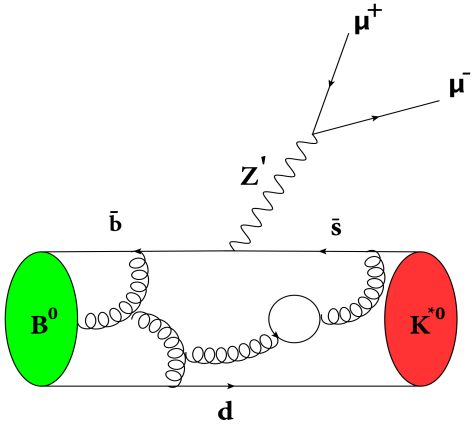


Pati-Salam extended $PS^3 \equiv PS_1 \times PS_2 \times PS_3$ with $PS_i = SU(4)_i \times [SU(2)_L]_i \times [SU(2)_R]_i$ (Bordone et al.) TeV LQ associated to 3rd gen.

Solutions to anomalies, generation of couplings & interplay with dark matter

Colourless vector $SU(2)_L$ triplets (W', B') or $U(1)'$ singlet

$$G \equiv SU(3)_c \times SU(2)_L \times U(1)_Y \times G_E$$

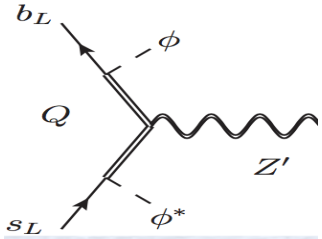


$G_E \equiv SU(2)_L$ could pot. explain anomalies ($R_K > 0.9$ & conflict with LHC searches)

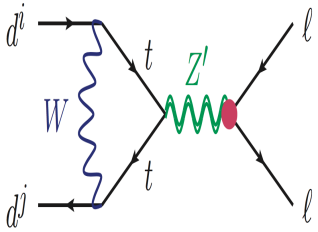
- $\bar{b}sZ'$ Quark FVC
- $Z'\ell\ell$ LFUV coupling

Generating Quark FV Coupling:

- Vector-like quarks: SM-VL couplings

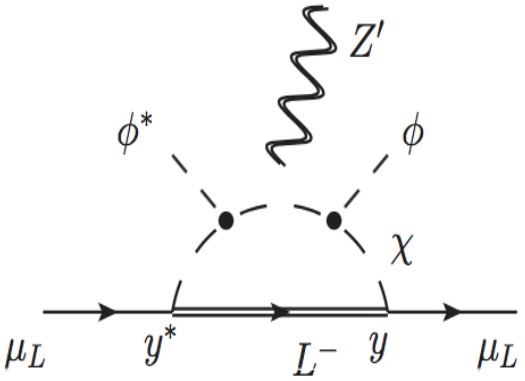


- Loop induced: SM FCNC, Z' penguins



Generating Couplings to Leptons:

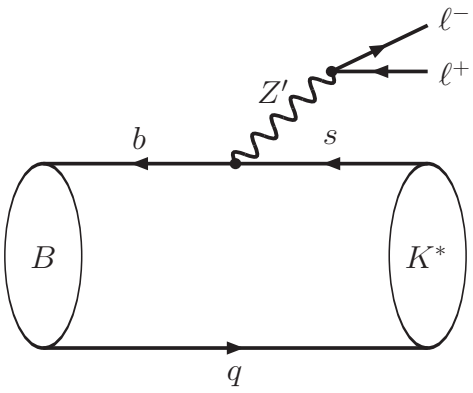
- Gauged $U(1)_{\mu-\tau}$ symmetry
- Loop induced with vector-like fermions

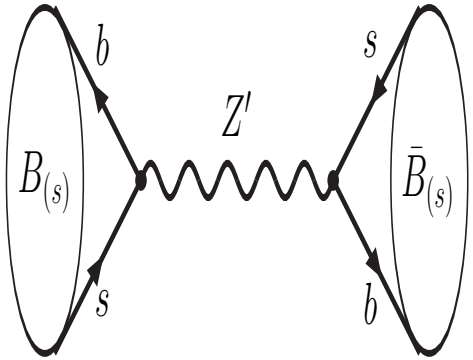


In [DMV'13] we proposed to explain the anomaly in $B \to K^* \mu\mu$ with a Z' **gauge boson** contributing to

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

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





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

The Wilson coefficients of the semileptonic operators are:

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

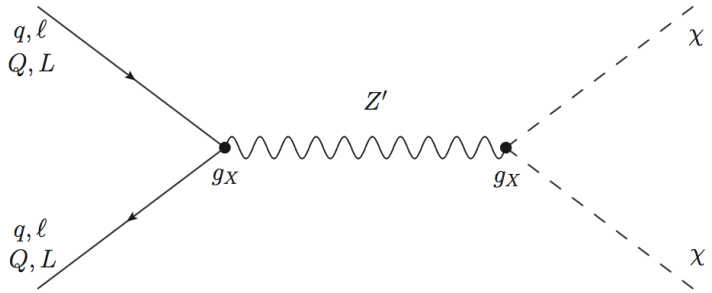
with the vector and axial couplings to muons: $\Delta^{\mu\mu}_{\mathbf{V},\mathbf{A}} = \Delta^{\mu\mu}_{\mathbf{R}} \pm \Delta^{\mu\mu}_{\mathbf{L}}$.

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

Other Z' constraints: $pp \to \mu\mu$, neutrino trident.

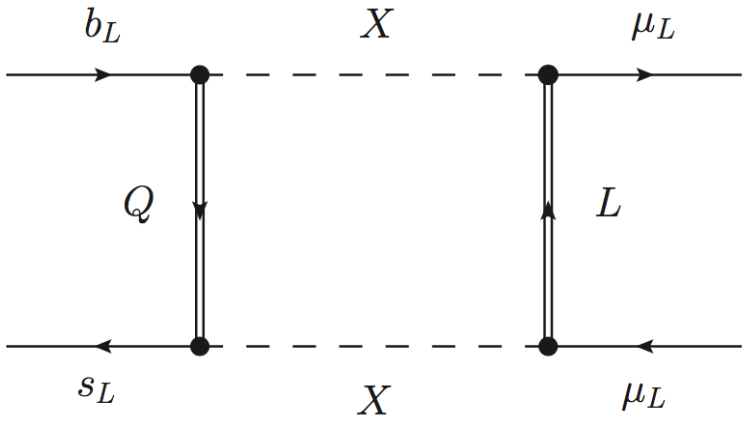
Link of $b \to s$ anomalies to dark matter:

- **Portal models:** Mediator for $b \to s\ell\ell$ anomalies also mediates dark matter production:



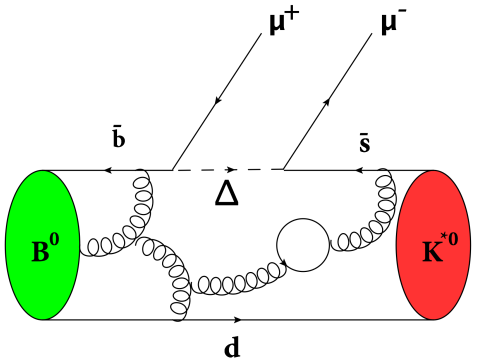
$\Rightarrow \chi$ dark matter particle: scalar field.
$\Rightarrow Q_{L,R}$ and $L_{L,R}$ vector-like fermions.
$\Rightarrow$ Left coupling same of $b \to s\ell\ell$ anomaly.

- **Loop models:** Models that induces the $b \to s$ transition via loops including the DM candidate. Two VL fermions Q and L and a complex scalar χ ($U(1)$ conserved $\Rightarrow \chi$ stable)



Link of $b \to s$ anomalies to hierarchy problem: compositeness

Leptoquarks

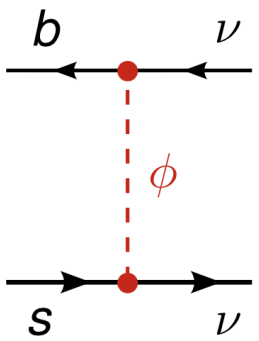


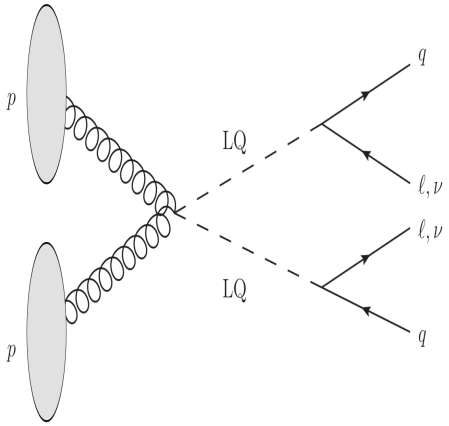
- Spin 1 (vector) $SU(2)_L$ singlet or triplet leptoquarks
- Spin 0 (scalar) $SU(2)_L$ singlet or triplet leptoquarks

They mainly point in all versions to $C_9 = -C_{10}$ (left-handed structure like in the SM)

Important constraints:

- $b \to s\nu\bar{\nu}$ (two scalars LQ can do the job)
- direct bounds (from 0.5-1 TeV)





Anomalies and explanations

i) $b \to s\ell\ell$: destructive NP wrt SM at 20% level.

Explanations: 1) Z' boson with FVC no-coupling to 1st gen. quarks and flavour symmetry to protect from K and D mixing. 2) Three LQS: S3, U1, and U3. Small coupling to e to avoid $\mu \to e\gamma$. B_s mixing loop level and LHC bounds weak since no coupling to 1st gen. quarks. 3) Loop effects with new S/F or top quarks (combined with Z' or LQ).

ii) $b \to c\tau\nu$: tree-level NP to generate 10% effect wrt SM

Explanations: 1) H^+, 2) W'^+ or 3) LQ. B_c lifetime and/or LHC searches disfavours 1) and 2). In case 3) careful with $B \to K^*\nu\nu$ and LHC searches: U1 or singlet-triplet (scalar LQs) model can do the job.

iii) CAA: θ_W parametrizes mixing among first 2 gen. quarks and dominates first row and column of CKM unitarity relations. $\sum_i |V_{ui}|^2 = 0.9985(5)$ and $\sum_i |V_{id}|^2 = 0.9970(18)$. V_{ud} from super-allowed β decays and V_{us} from K and τ decays. Probable responsible V_{ud}.

Explanations: modified Fermi constant 1) direct modification of β-decays: W^+ or LQ. 2) direct modification of μ decay: singly charged $SU(2)_L$ singlet scalar, a W'^+ or Z' with FVC. 3) $W - \mu\nu$ modified coupling: vector-like leptons and 4) $W - u - d$ modified coupling: vector-like quarks.

iv) $q\bar{q} \to e^+e^-$: non-resonant electrons (CMS) found excess in electrons why muons are SM-like.

Explanations: NP coupling to 1st gen. quarks and e^- wit $\mathcal{O}(1)$ couplings and masses around 10 TeV. Z' or a LQ coupling to e^- and 1st gen. quarks (to explain also $b \to s\ell\ell$ μ couples to 2nd and 3rd generation).

v) ΔA_{FB} of $B \to D^*\mu\nu$ and $B \to D^*e\nu$ expected zero while 4σ tension found.

Explanations: Require tensor contributions that can be generated by two scalar LQs and the singlet gives good fit to data.

vi) $\tau \to \mu\nu\bar{\nu}$: Combining ratios

$$\left.\frac{\mathcal{A}\left[\tau \to \mu\nu\bar{\nu}\right]}{\mathcal{A}\left[\mu \to e\nu\bar{\nu}\right]}\right|_{\rm EXP} = 1.0029 \pm 0.0014\,,$$
$$\left.\frac{\mathcal{A}\left[\tau \to \mu\nu\bar{\nu}\right]}{\mathcal{A}\left[\tau \to e\nu\bar{\nu}\right]}\right|_{\rm EXP} = 1.0018 \pm 0.0014\,,$$
$$\left.\frac{\mathcal{A}\left[\tau \to e\nu\bar{\nu}\right]}{\mathcal{A}\left[\mu \to e\nu\bar{\nu}\right]}\right|_{\rm EXP} = 1.0010 \pm 0.0014\,,$$

with correlations a 2σ preference for constructive NP at per-mille level in $\tau \to \mu\nu\nu$. **Explanations**: similar to CAA, singlet $SU(2)_L$ scalar, W'^+ or FVC Z'. Modification of $W - \tau - \nu$ via mixing with VLLeptons or W'^+. Box with Z' coupling to μ and τ.

2D and 6D Scenarios for $\mathcal{C}_{i\mu}$

	All			LFUV		
2D Hyp.	Best fit	Pull_{SM}	p-value	Best fit	Pull_{SM}	p-value
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$	(-0.92,+0.17)	6.8	25.6 %	(-0.16,+0.55)	4.7	71.2 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu})$	(-1.12,+0.36)	6.9	27.4 %	(-1.82,+1.09)	4.5	60.2 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10'\mu})$	(-1.15,-0.26)	7.1	31.8 %	(-1.88,-0.59)	5.0	88.1 %
Scn-R $(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$	(-1.15,+0.17)	7.1	31.1 %	(-2.13,+0.50)	5.0	89.4 %
$(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$	(-0.47,+0.07)	6.3	16.8 %	(-0.48,+0.15)	4.8	79.6 %

- No change in the hierarchy of scenarios w.r.t. 2020.
- From last two rows: Vector preference in left sector ($C_{9\mu}^{\text{NP}}$) (vs $C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$) and $C_{9'\mu} = -C_{10'\mu}$ preference in right sector.

	$\mathcal{C}_7^{\text{NP}}$	$\mathcal{C}_{9\mu}^{\text{NP}}$	$\mathcal{C}_{10\mu}^{\text{NP}}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Bfp	+0.00	-1.08	+0.15	+0.00	+0.16	-0.18
$1\,\sigma$	$[-0.02, +0.01]$	$[-1.25, -0.90]$	$[+0.02, +0.28]$	$[-0.01, +0.02]$	$[-0.20, +0.53]$	$[-0.36, +0.02]$
$2\,\sigma$	$[-0.04, +0.03]$	$[-1.41, -0.72]$	$[-0.10, +0.42]$	$[-0.03, +0.03]$	$[-0.56, +0.92]$	$[-0.54, +0.22]$

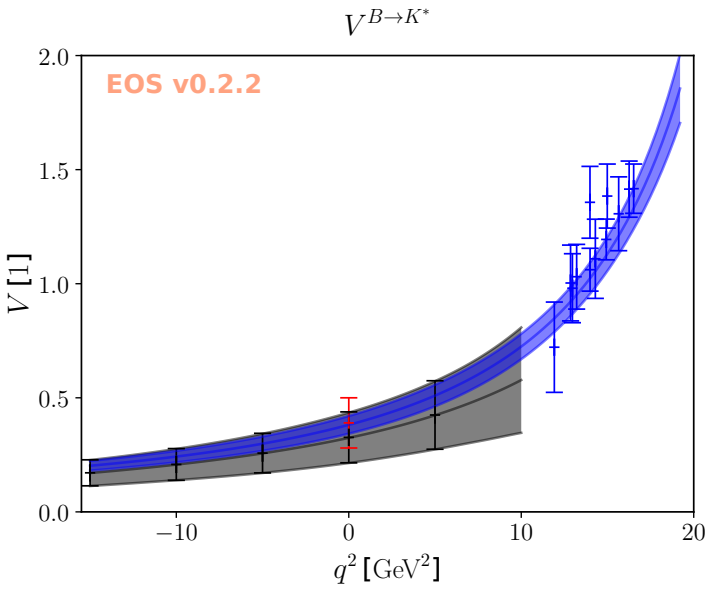
- Pull_{SM}: 5.1σ [2019] $\rightarrow$ 5.8σ [2020] $\rightarrow$ 6.3σ [2022] (27.8%)
- 6D Fit shows coherence and stability with time.

Hadronic uncertainties: form factors

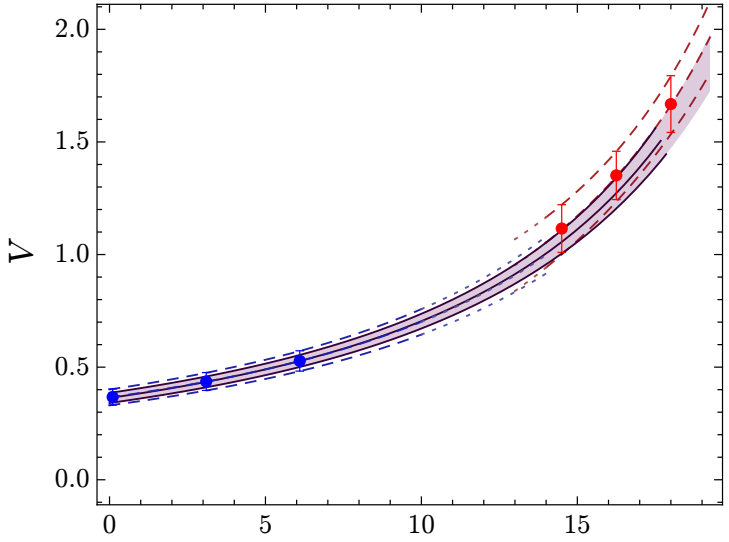
3 form factors for K, 7 form factors for K^* and ϕ

- low recoil: lattice QCD [Horgan, Liu, Meinel, Wingate; HPQCD collab]
- large recoil: Light-Cone Sum Rules (B-meson or light-meson DAs)

[Khodjamirian, Mannel, Pivovarov, Wang; Bharucha, Straub, Zwicky; Gubernari, Kokulu, van Dyk]



B-meson LCSR + lattice



Light-meson LCSR + lattice

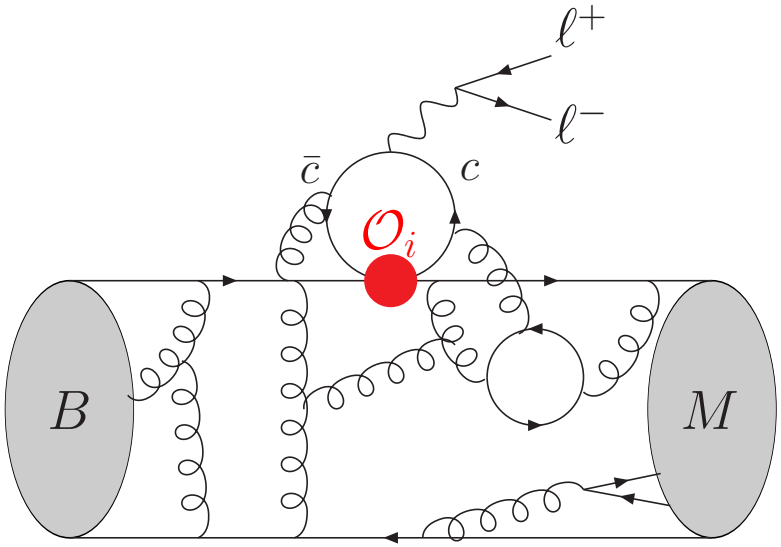
- correlations among the form factors needed
  - known from direct determination and/or combined fit to low and large recoils [PS]
  - recovered from EFT with $m_b \to \infty + O(\alpha_s) + O(1/m_b)$ [QM]

[Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]

- optimised observables P_i to reduce the impact of form factor uncertainties

Hadronic uncertainties: charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- depends on q^2, lepton univ.
- quark-hadron duality approx at large q^2 (syst of few %)



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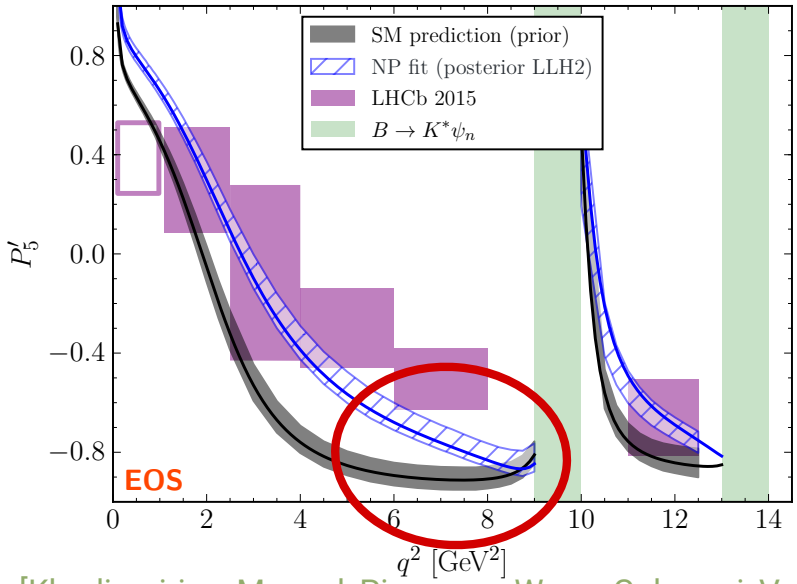


[Khodjamirian, Mannel, Pivovarov, Wang; Gubenari, Van Dyk]

(see talk by Gubenari)

Several approaches agree at low-q^2

- LCSR estimates
- order of magnitude estimate for the fits (LCSR or Λ/m_b), check with bin-by-bin fits we include a nuisance parameter s_i to allow for constructive/destructive interference between charm and short-distance for each amplitude widening theo uncertainties [Crivellin, Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]
- dispersive representation + $J/\psi, \psi(2S)$ data [Bobeth, Chrzaszcz, van Dyk, Virto]

Is charm-loop **overestimated** instead of **underestimated**?

Theoretical inputs

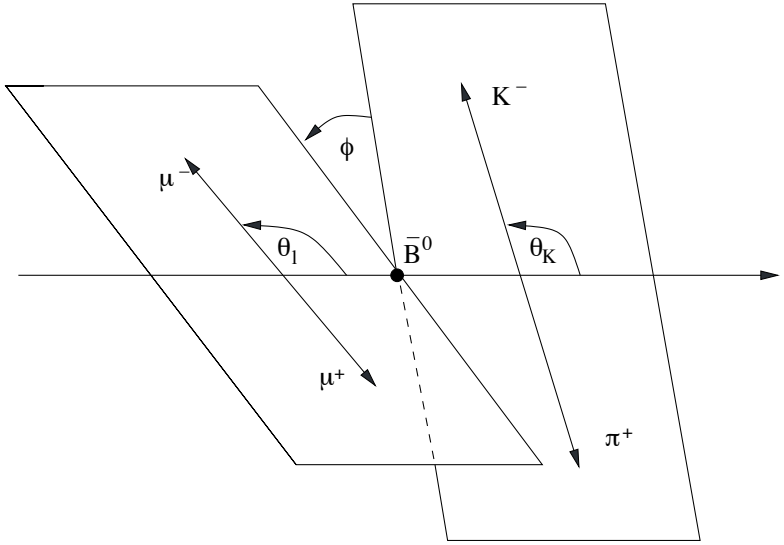
- **Form factors:** B-meson DA LCSR + lattice + EFT for correlations
- **Charm-loop corrections**: Perturbative contribution + magnitude of of long-distance contrib inspired by [Khodjamirian, Mannel, Pivovarov, Wang]
- **Quark-duality violation at high** q^2: conservative 10% effect at the level of the amplitude

  (explicit estimates [Feldman, Buchalla] at the level of 2%)
- $Br(B_s \to \mu\mu)$ modified to include latest corrections from

  [Misiak ; Beneke, Bobeth, Szafron]
- $Br(B^+ \to K^{*+}\ell\ell)$ and P_i^+ include mass and lifetime differences, annihilation graphs, hard spectator interactions with $\mathcal{O}_8$ and $\mathcal{O}_{1-6}$

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

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



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

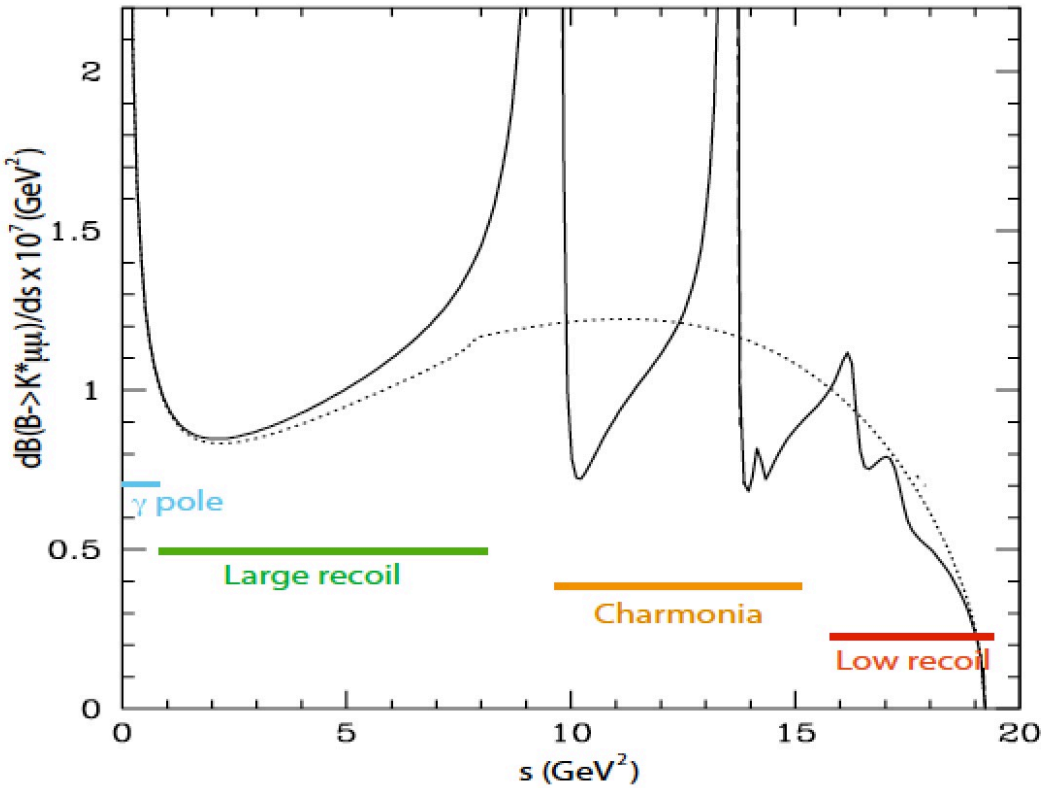
$\mathbf{q^2}$: dilepton invariant mass square.

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

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

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

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

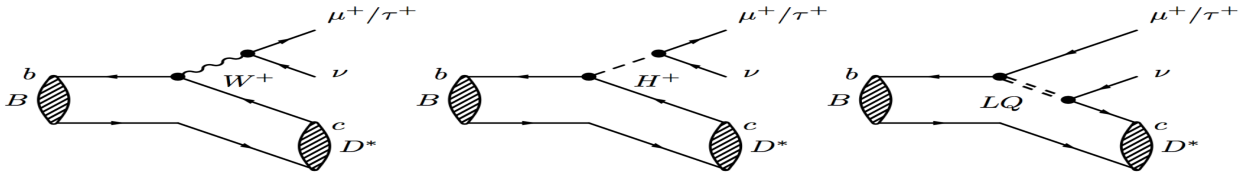


- **very large** K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2): γ almost real.
- **large** K^***-recoil/low-q**^{2}: $E_{K^*} \gg \Lambda_{QCD}$ or $4m_\ell^2 \leq q^2 < 9$ GeV^2: LCSR-FF
- charmonium region ($q^2 = m^2_{J/\Psi}, \ldots$) betwen $9 < q^2 < 14$ GeV^2.
- **low** K^***-recoil/large-q**^{2}: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

Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by about 3σ.

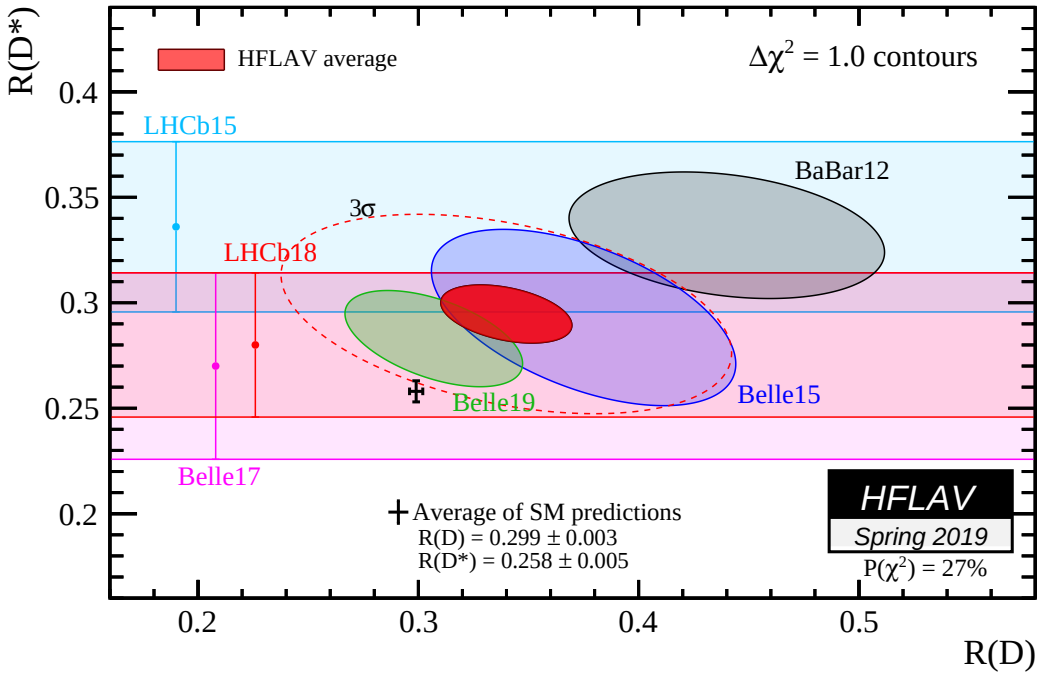
BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529, arXiv:1904.08794



SM NP

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

$$\ell \in \{e, \mu\}$$



HFLAV, hflav.web.cern.ch

Setup

- Likelihood taking into account experimental and theoretical uncertainties and correlations in Gaussian approximation

[Algueró, Capdevila, Crivellin, SDG, Masjuan, Matias, Novoa-Brunet, Virto]

We fit $C_i = C_i^{\rm SM} + C_i^{\rm NP}$

Two statistical quantities of interest to asses a NP scenario/hypothesis:

- p-value of a given hypothesis: $\chi^2_{\rm min}$ considering N_{dof} (in %)
  goodness of fit: does the hypothesis give an overall good fit ?
  and if not, can we exclude it ?
- Pull$_{\rm SM}$: $\chi^2(\mathcal{C}_i = 0) - \chi^2_{min}$ considering N_{dof} (in σ units)
  metrology: how well does the hypothesis solve SM deviations ?

Scale of New physics

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

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

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

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

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

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

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

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

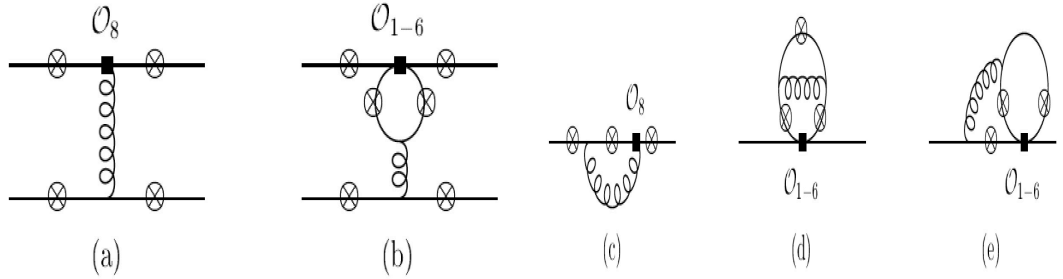
Solution $C_9^{\rm NP} \sim -1.1$ (scale is $\sim$ numerator) or $C_9^{\rm NP} = -C_{10}^{\rm NP} \sim -0.6$ (30 % higher scale).

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

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

1 Computed in i-QCDF + KMPW+ 4-types of corrections.

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

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

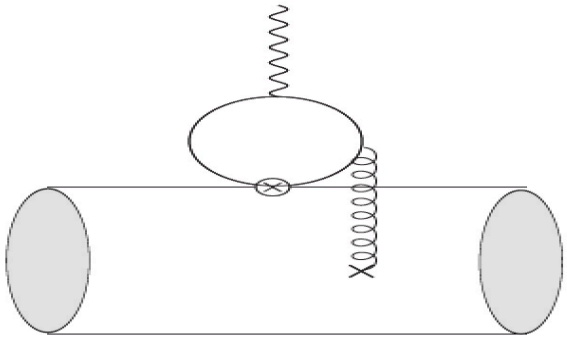
Long-distance contributions from $c\bar{c}$ loops where the lepton pair is created by an electromagnetic current.

2 KMPW is the only real computation of long-distance charm.

$$C_9^{\text{eff i}} = C_9^{\text{eff}}{}_{\text{SM pert}}(q^2) + C_9^{\text{NP}} + s_i \delta C_9^{c\bar{c}(i)}{}_{\text{KMPW}}(q^2)$$

KMPW implies $s_i = 1$, but we vary $s_i = 0 \pm 1$, $i = 0, \perp, \parallel$.

- expansion in $\Lambda^2/(q^2 - 4m_c^2)$ computed for $q^2 < 0$.
- extrapolated through dispersion relation



The L-observable; model independent interpretation

$$H_{\rm eff}^{b\to s} = \frac{G_F}{\sqrt{2}} \sum_{p=c,u} \lambda_p^{(q)} \left(\mathscr{C}_{1s}^p Q_{1s}^p + \mathscr{C}_{2s}^p Q_{2s}^p + \sum_{i=3\ldots10} \mathscr{C}_{is} Q_{is} + \mathscr{C}_{7\gamma s} Q_{7\gamma s} + \mathscr{C}_{8gs} Q_{8gs} \right).$$

We identify three dominant operators:

$$Q_{1s}^p = (\bar{p}b)_{V-A}(\bar{s}p)_{V-A}$$

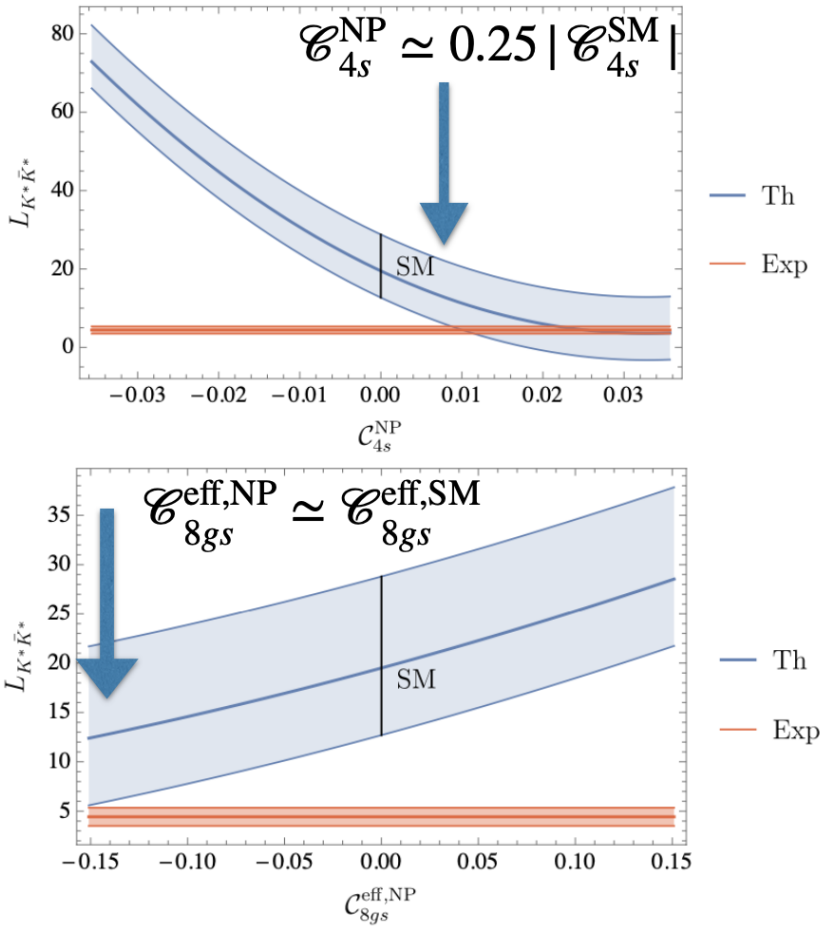
60% too large (10% max. Lenz&al'20)

$$Q_{4s} = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$$

$$Q_{8gs} = \frac{-g_s}{8\pi^2} m_b \, \bar{s}\sigma_{\mu\nu}(1+\gamma_5)G^{\mu\nu} b \,,$$

In SM at $\mu = 4.2\,\mathrm{GeV}$**:**

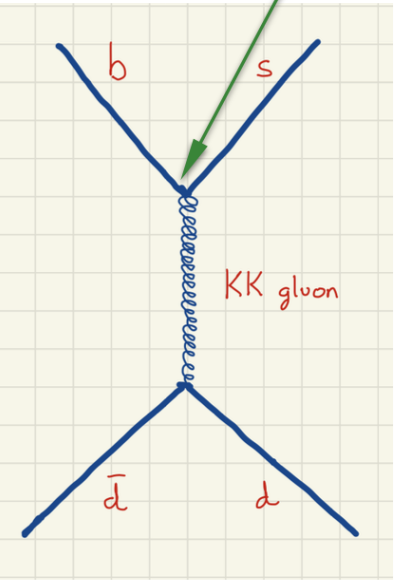
$$\mathscr{C}_{4s}^{SM} = -0.036 \qquad \mathscr{C}_{8}^{eff\,SM} = -0.151$$



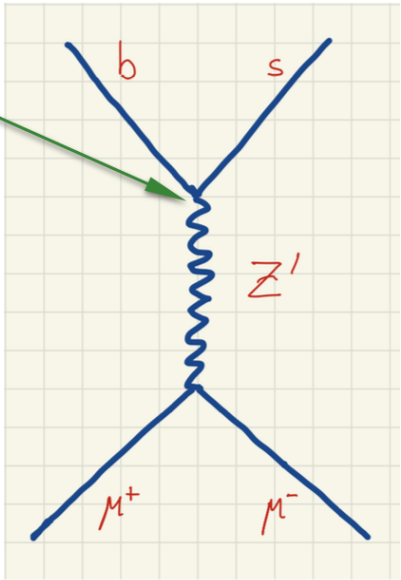
The L-observable; simplified New Physics models

Possible "link" to $b \to s\ell\ell$ anomalies…

degree of compositeness of b and s



KK gluon part of the spectrum of composite/ extra-dimensional model + Z' **boson**



Explain $b \to s\ell^+\ell^-$ anomalies.

Explain $L_{K^*K^*}$