"B-Anomalies" in $b \to c\tau\overline{\nu}$ and $b \to s\ell\bar{\ell}$

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GDR Lectures
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Outline

- $b \to c\tau\overline{\nu}$
- $b \to s\ell\overline{\ell}$
- New physics interpretations

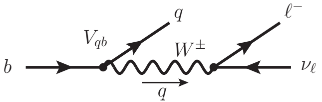
$R(D)$ and $R(D^*)$

$b \to c\tau\overline{\nu}$ vs. $b \to c\ell\overline{\nu}$

"LFU ratios" in exclusive $B \to D^{(*)} \ell \overline{\nu}_\ell$

Remember in SM EFT given by

EFT for $b \to c \ell \overline{\nu}_\ell$ with $\ell = e, \mu, \tau$



$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{QCD}\times\text{QED}} - \frac{4\mathcal{G}_F}{\sqrt{2}} V_{qb} C_{V_L} Q_{V_L}$$

$$Q_{V_L} \equiv [\overline{c}\gamma_\mu P_L b][\overline{\ell}\gamma^\mu P_L \nu_\ell]$$

$\Rightarrow$ in principle each $C_{V_L} Q_{V_L} \to C_{V_L}^{\ell\nu} Q_{V_L}^{\ell\nu}$ should carry indices for ℓ and $\nu_{\ell'}$,

but in SM $C_{V_L}^{\ell\nu} = C_{V_L}$ **lepton-flavor-universal (LFU)**

Can test LFU in ratios involving different $\ell = e, \mu, \tau$

$$R^{\ell\ell'}(M) \equiv \frac{\int_{m_\ell^2}^{(m_B - m_M)^2} dq^2 \, \frac{d\mathcal{B}[\overline{B} \to M\ell\overline{\nu}]}{dq^2}}{\int_{m_{\ell'}^2}^{(m_B - m_M)^2} dq^2 \, \frac{d\mathcal{B}[\overline{B} \to M\ell'\overline{\nu}]}{dq^2}}$$

- note different phase-space integral
- in SM overall factor $\propto \mathcal{G}_F^2 |V_{cb} C_{V_L}|^2$ cancels
- same $B \to M$ FF's enter num & den, uncertainties in FF-normalizations cancel

For $\ell = \tau$ and $\ell' = e + \mu$ (light-lepton average) they are known for $M = D \to R(D)$

and $M = D^* \to R(D^*)$

SM predictions of $R(D)$ and $R(D^*)$

Prediction requires knowledge of form factors (shape) $\Rightarrow$ two strategies

A) use **only theory input** from LQCD, LCSR and unitarity bounds (UB) + HQET constraints

B) **fit FF-parameters from data** of $B \to D^{(*)}\ell\overline{\nu}$ for light $\ell = e + \mu$,
assuming new physics only in $\ell = \tau$

$\Rightarrow$ in the past combination of A) + B), but clearly prefer A)

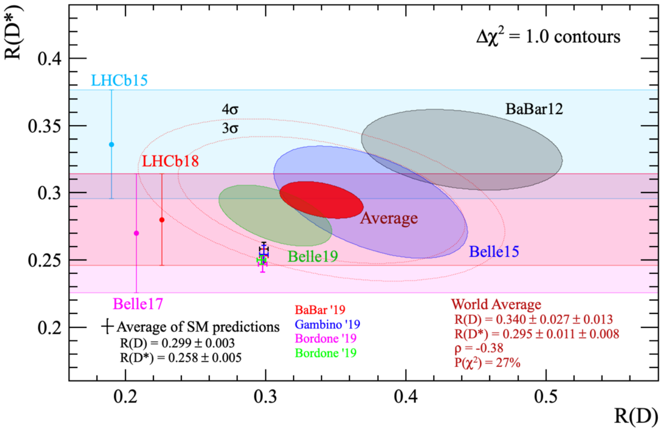
SM predictions	$R(D)$	$R(D^*)$	Ref.
LCSR only	0.269 ± 0.100	0.242 ± 0.048	[GKvD'18]
LQCD only	0.300 ± 0.008	—	[HPQCD'15]
LCSR + LQCD	0.296 ± 0.006	0.256 ± 0.020	[GKvD'18]
LCSR + LQCD + UB + HQET	0.2989 ± 0.0032	0.2472 ± 0.0050	[BGJvD'19]

[HPQCD'15 = HPQCD collaboration 1505.03925]
[GKvD'18 = Gubernari/Kokulu/van Dyk 1811.00983]
[BGJvD'19 = Bordone/Gubernari/Jung/van Dyk 1912.0]

provide method A) results in BGL parametrization →

- LQCD calculations of $B \to D^*$ FFs away from q^2_{max} are work in progress
- Also $R(D_s) = 0.2970 \pm 0.0034$ and $R(D_s^*) = 0.2450 \pm 0.0082$ [BGJvD'19]
- also $R(J\psi)$, $R(\Lambda_c)$, $R(X_c)$ (partial predictions)

Measurements of $R(D)$ and $R(D^*)$



see details and updates at **https://hflav.web.cern.ch**

- measurements from BaBar, Belle and LHCb with different tags
- HFLAV states 3.1 σ deviation from SM for combination $R(D)$ & $R(D^*)$
  $\Rightarrow$ would increase to 3.8 σ with SM prediction from LCSR + LQCD + UB + HQET
- single deviations from SM: 1.4 σ for $R(D)$ and 2.5 σ for $R(D^*)$

Beyond SM operator basis

WEFT approach

(assuming no light ν_R)

in SM: $C_{V_L} = 1$, $C_a = 0$ ($a = V_R, S_{L,R}, T$)

$$\mathcal{L}_{\text{EFT}} = -\frac{4\mathcal{G}_F}{\sqrt{2}} V_{cb} \sum_{a=1}^{5} C_a \mathcal{O}_a$$

$$\mathcal{O}_{V_{L(R)}} = [\bar{c}\gamma_\mu P_{L(R)} b][\bar{\tau}\gamma^\mu \nu]$$

$$\mathcal{O}_{S_{L(R)}} = [\bar{c} P_{L(R)} b][\bar{\tau}\nu]$$

$$\mathcal{O}_T = [\bar{c}\sigma_{\mu\nu} P_L b][\bar{\tau}\sigma^{\mu\nu}\nu]$$

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Global fit of $b \to c\tau\bar{\nu}$ only

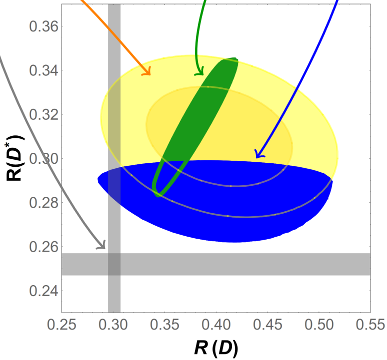
Experiment

SM prediction

vector coupling $a = V_L$

scalar couplings $a = S_{L,R}$

[Celis/Jung/Li/Pich 1612.07757]



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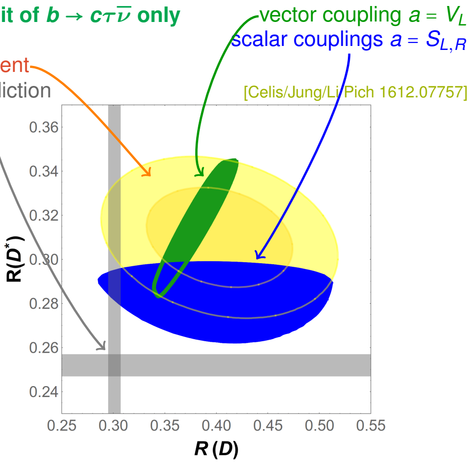
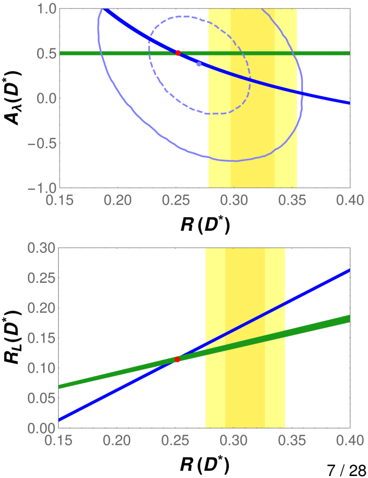
Global fit of $b \to c\tau\bar{\nu}$ only

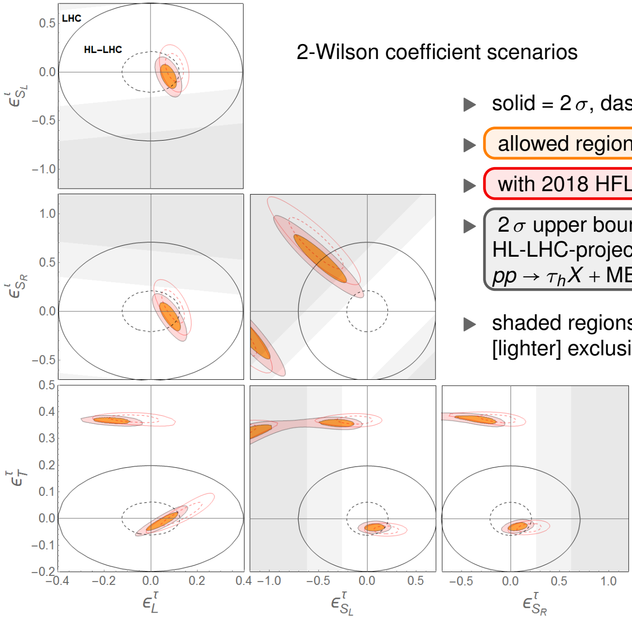


Predictions for $A_\lambda(D^*)$ and R_L



Fits of Wilson coefficients 2019

[Shi/Geng/Grinstein/Jäger/Martin-Camalich 1905.08498]



2-Wilson coefficient scenarios

- solid = 2 σ, dashed = 1 σ
- allowed regions from $R(D)$ and $R(D^*)$
- with 2018 HFLAV results
- 2 σ upper bound from LHC [solid] and HL-LHC-projection [dashed] on $pp \to \tau_h X + \text{MET}$
- shaded regions = 30 % [darker] and 10 % [lighter] exclusion limits from $\mathcal{B}(B_c \to \tau\nu)$

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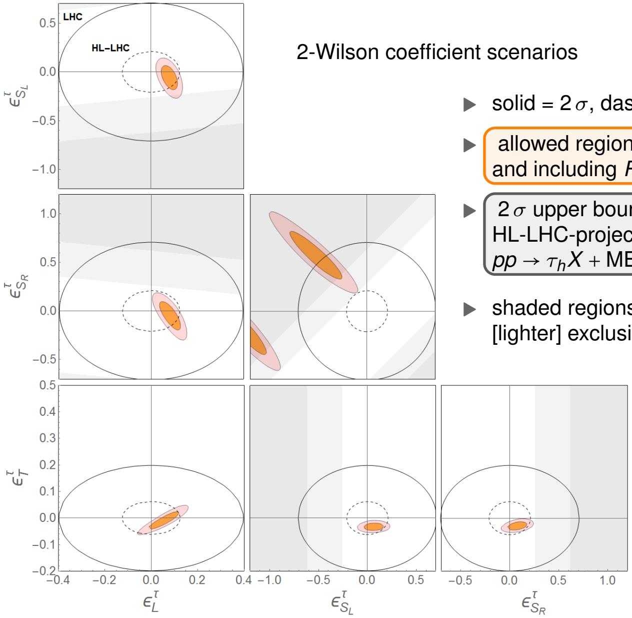

2-Wilson coefficient scenarios

- solid = 2 σ, dashed = 1 σ
- allowed regions from $R(D)$ and $R(D^*)$, and including $R(J/\psi)$, $P_\tau(D^*)$, $F_L(D^*)$
- 2 σ upper bound from LHC [solid] and HL-LHC-projection [dashed] on $pp \to \tau_h X + \text{MET}$
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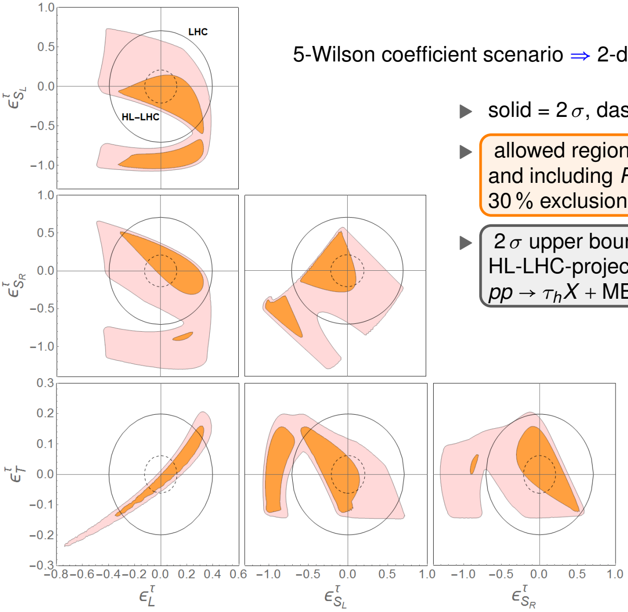


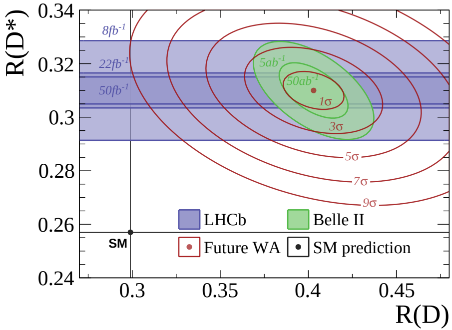
5-Wilson coefficient scenario $\Rightarrow$ 2-dim regions, others marginalized

- solid = $2\,\sigma$, dashed = $1\,\sigma$
- allowed regions from $R(D)$ and $R(D^*)$, and including $R(J/\psi)$, $P_\tau(D^*)$, $F_L(D^*)$, 30 % exclusion limits from $\mathcal{B}(B_c \to \tau\nu)$
- $2\,\sigma$ upper bound from LHC [solid] and HL-LHC-projection [dashed] on $pp \to \tau_h X + \text{MET}$

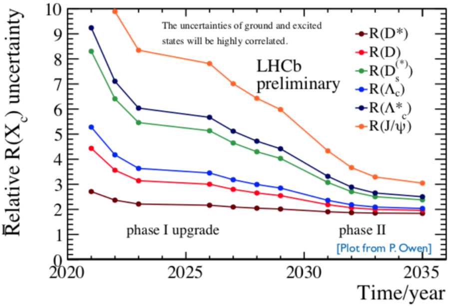
Prospects $b \to c\tau\nu$

[Albrecht/Bernlochner/Kenzie/Reichert/Straub/Tully 1709.10308]

Obs	SM Prediction	Current World Average	Current Uncertainty	Projected Uncertainty				
				Belle		**LHCb**		
				5/ab	50/ab	8/fb	22/fb	50/fb
$R_D^{\tau/\mu}$	0.299 ± 0.003	0.403 ± 0.047	11.6%	5.6%	3.2%	—	—	—
$R_{D^*}^{\tau/\mu}$	0.257 ± 0.003	0.310 ± 0.017	5.5%	3.2%	2.2%	3.6%	2.1%	1.6%



[Albrecht/Bernlochner/Kenzie/Reichert/Straub/Tully 1709.10308]



[Patrick Owen @ LHCb Upgrade WS, Elba, 2017]

Exclusive $b \to s\ell\bar{\ell}$

$B \to K^{(*)}\ell\bar{\ell}, \ldots$

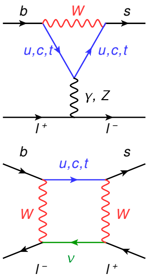
EFT for $b \to q + (\gamma, \ell\bar{\ell})$ in SM

$q = d, s$

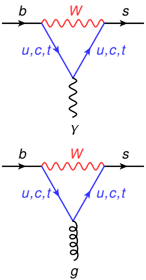
$$\mathcal{L}_{\Delta B=1} \sim V_{tb} V_{tq}^* \Big[\sum_{9,10} C_i^{\ell\bar{\ell}} Q_i^{\ell\bar{\ell}} + \sum_{7\gamma,8g} C_i Q_i + \mathrm{CC} + (\text{QCD \& QED-peng}) \Big] + V_{ub} V_{uq}^* \big[\mathrm{CC}^u - \mathrm{CC}^c \big]$$

In the SM various operators

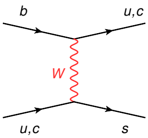
semi-leptonic



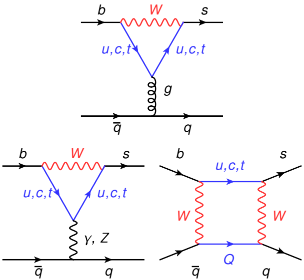
QCD & QED -dipole



charged current



QCD & QED -penguin



EFT for $b \to q + (\gamma, \ell\bar{\ell})$ in SM

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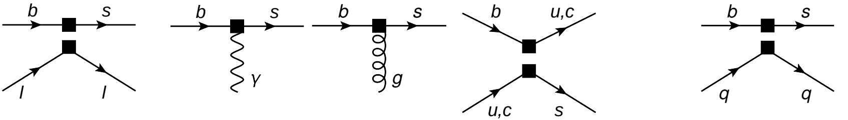
$$+ V_{ub} V_{uq}^* \Big[\text{CC}^u - \text{CC}^c \Big]$$

In the SM various operators

semi-leptonic | QCD & QED -dipole | charged current | QCD & QED -penguin



C_i = **Wilson coefficients:** short-dist. param's (heavy masses $m_t, m_W, \ldots$ – CKM factored out) and leading logarithmic QCD-corrections to all orders in α_s

$\Rightarrow$ in SM known up to NNLO QCD and NLO EW/QED

Q_i = **dim-6 operators:** flavor-changing coupling of light quarks

Theory of exclusive $b \to (d, s)\ell\bar{\ell}$

Dipole & Semileptonic op's

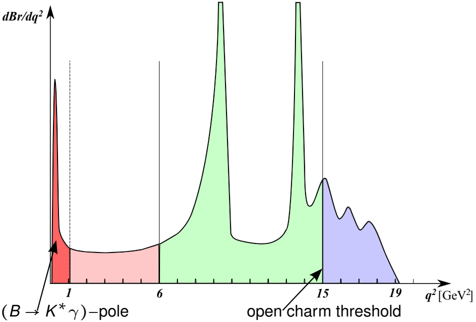
$$Q_{7\gamma(7\gamma')} = m_b[\bar{q}\,\sigma^{\mu\nu} P_{R(L)}\, b]F_{\mu\nu}$$

$$Q^{\ell\ell}_{9(9')} = [\bar{q}\,\gamma^{\mu} P_{L(R)}\, b][\bar{\ell}\,\gamma_{\mu}\,\ell]$$

$$Q^{\ell\ell}_{10(10')} = [\bar{q}\,\gamma^{\mu} P_{L(R)}\, b][\bar{\ell}\,\gamma_{\mu}\gamma_5\,\ell]$$

Factorisation into form factors (@ LO QED)

$\Rightarrow$ No conceptual problems !!!



@ low q^2: FF's from LCSR — $B \to K, \pi$
(10 – 15)% accuracy — $B \to K^*$

[Ball/Zwicky hep-ph/0406232, Khodjamirian et al. 1006.4945
Bharucha/Straub/Zwicky 1503.05534]

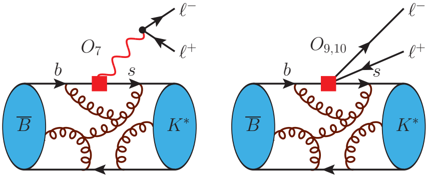
@ high q^2: FF's from lattice — $B \to K, \pi$
(6 – 9)% accuracy — $B \to K^*$

[Bouchard et al. 1306.2384
Horgan/Liu/Meinel/Wingate 1310.3722 + 1501.00367]

FF relations at low & high q^2

- allow to relate FF's $\Rightarrow$ reduce their number
- valid up to $\Lambda_{\rm QCD}/m_b \simeq 0.5/4 \approx 13\%$

$\Rightarrow$ "optimized observables" in $B_q \to V\ell\bar{\ell}$



Theory of exclusive $b \to (d,s)\ell\bar{\ell}$

Nonleptonic

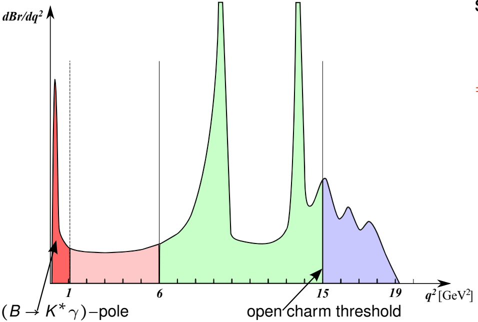
$$Q_{(1)2} = [\bar{q}\gamma^\mu P_L (T^a)\, c][\bar{c}\gamma_\mu P_L (T^a)\, b]$$

$$Q_{3,4,5,6} = [\bar{q}\Gamma_{sb} P_L (T^a)\, b] \sum_q [\bar{q}\Gamma_{qq} (T^a)\, q]$$

$$Q_{8g(8g')} = m_b [\bar{q}\sigma^{\mu\nu} P_{R(L)} T^a\, b] G^a_{\mu\nu}$$

at LO in QED

$$\int d^4x\, e^{i\,q\cdot x} \left\langle M_\lambda^{(*)} \middle| \mathrm{T}\left\{ j_\mu^{\mathrm{em}}(x), \sum_i C_i Q_i(0) \right\} \middle| \overline{B} \right\rangle$$



different approaches at

Large Recoil (low-q^2)

1) QCD factorization or SCET
2) LCSR
3) non-local OPE of $\bar{c}c$-tails

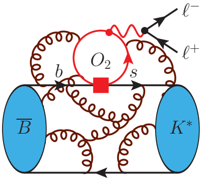
[Beneke/Feldmann/Seidel hep-ph/0106067 + 0412400
Lyon/Zwicky et al. 1212.2242 + 1305.4797
Khodjamirian et al. 1006.4945 + 1211.0234 + 1506.07760]

Low Recoil (high-q^2)

local OPE (+ HQET) $\Rightarrow$ theory only for sufficiently large q^2-integrated obs's

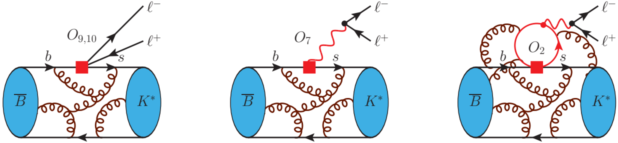
[Grinstein/Pirjol hep-ph/0404250
Beylich/Buchalla/Feldmann 1101.5118]

$\Rightarrow$ least understood theoretical uncertainties



Helicity amplitudes for $B \to K^* \ell\bar{\ell}$

The $B \to K^* \ell\bar{\ell}$ **helicity amplitudes** ($\lambda = \perp, \parallel, 0$) in terms ofWilson coefficients and hadronic MEs



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

- Wilson coefficients
- local form factors $\mathcal{F}_\lambda^{(T)}(q^2)$ (for quasistable K^*)
- nonlocal ME of hadronic operators

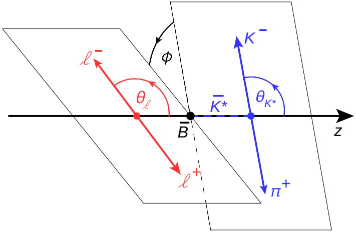
$$\mathcal{H}_\lambda(q^2) = i\,\mathcal{P}_\lambda^\mu \int d^4x\, e^{i\,q\cdot x} \left\langle M_\lambda^{(*)} \middle| \mathrm{T}\left\{ j_\mu^{\mathrm{em}}(x), \sum_i C_i Q_i(0) \right\} \middle| \overline{B} \right\rangle$$

Observables in terms of helicity amplitudes are

$$J_i \propto \mathrm{Re}, \mathrm{Im} \left[A_{\lambda_1}^L \left(A_{\lambda_2}^L\right)^* \pm A_{\lambda_1}^R \left(A_{\lambda_2}^R\right)^* \right]$$

Angular distributions $B \to V(\to P_1 P_2)\ell\bar{\ell}$

$$\frac{d^4\Gamma[B \to K^*(\to K\pi)\ell\bar{\ell}]}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} \simeq J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K$$
$$+(J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell + J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + J_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_\ell + J_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi$$



- with $J_i(q^2)$ from $\overline{B} \to \overline{K}^* \ell\bar{\ell}$ and $\bar{J}_i(q^2)$ from $B \to K^*\ell\bar{\ell}$ can measure 12 CPav + 12 CPasy **angular ob's**
  - $\Rightarrow$ key to constrain all Wilson coefficients
- LHCb started to measure them in 2013, several updates since then

"Optimized" observables $\Rightarrow$ reduced FF sensitivity

- guided by large energy limit @ low-q^2 and Isgur-Wise @ high-q^2 FF-relations
- FF's cancel up to corrections $\sim \Lambda_{\rm QCD}/m_b$
- no such cancellation of $c\bar{c}$-hadronic effects

Angular distributions $B \to V(\to P_1 P_2)\ell\bar{\ell}$

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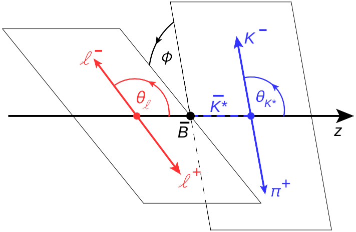


"Optimized" observables = ratios of angular observables J_i

@ low q^2

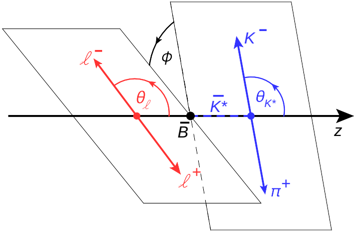
[Krüger/Matias hep-ph/0502060, Egede/Hurth/Matias/Ramon/Reece arXiv:0807.2589 + 1005.0571]
[Becirevic/Schneider arXiv:1106.3283]
[Matias/Mescia/Ramon/Virto arXiv:1202.4266]
[Descotes-Genon/Matias/Ramon/Virto arXiv:1207.2753]

$$A_T^{(2)} \equiv P_1 \equiv \frac{J_3}{2J_{2s}} \qquad A_T^{(\mathrm{re})} \equiv 2P_2 \equiv \frac{J_{6s}}{4J_{2s}} \qquad A_T^{(\mathrm{im})} \equiv -2P_3 \equiv \frac{J_9}{2J_{2s}}$$

$$P_4' \equiv \frac{J_4}{\sqrt{-J_{2c}J_{2s}}} \qquad P_5' \equiv \frac{J_5/2}{\sqrt{-J_{2c}J_{2s}}} \qquad P_6' \equiv \frac{-J_7/2}{\sqrt{-J_{2c}J_{2s}}} \qquad P_8' \equiv \frac{-J_8}{\sqrt{-J_{2c}J_{2s}}}$$

Angular distributions $B \to V(\to P_1 P_2)\ell\bar{\ell}$

$$\frac{d^4\Gamma[B \to K^*(\to K\pi)\ell\bar{\ell}]}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} \simeq J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K$$
$$+(J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi$$
$$+J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi$$
$$+J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$$



"Optimized" observables = ratios of angular observables J_i

@ high q^2

[CB/Hiller/van Dyk arXiv:1006.5013]
[Matias/Mescia/Ramon/Virto arXiv:1202.4266]
[CB/Hiller/van Dyk arXiv:1212.2321]

$$H_T^{(1)} \equiv P_4 \equiv \frac{\sqrt{2} J_4}{\sqrt{-J_{2c}(2J_{2s} - J_3)}}$$

$$H_T^{(2)} \equiv P_5 \equiv \frac{J_5/\sqrt{2}}{\sqrt{-J_{2c}(2J_{2s} + J_3)}} \qquad H_T^{(3)} \equiv \frac{J_{6s}/2}{\sqrt{(2J_{2s})^2 - (J_3)^2}}$$

$$H_T^{(4)} \equiv Q \equiv \frac{\sqrt{2} J_8}{\sqrt{-J_{2c}(2J_{2s} + J_3)}} \qquad H_T^{(5)} \equiv \frac{-J_9}{\sqrt{(2J_{2s})^2 - (J_3)^2}}$$

LFU ratios for $\overline{B} \to M\ell\bar{\ell}$ for μ vs. e

$$R_M^{\ell/\ell'}[q_a^2, q_b^2] \equiv \frac{\displaystyle\int_{q_a^2}^{q_b^2} dq^2 \frac{d\mathcal{B}[\overline{B} \to M\ell\bar{\ell}]}{dq^2}}{\displaystyle\int_{q_a^2}^{q_b^2} dq^2 \frac{d\mathcal{B}[\overline{B} \to M\ell'\bar{\ell}']}{dq^2}}$$

in SM cancellations of

- CKM and hadronic uncertainties
- experimental systematics
- $M = K, K^*, \phi, X_s, \ldots$

[Hiller/Krüger hep-ph/0310219]

- in SM "universality" $R_M^{\mu/e} \approx 1 + \mathcal{O}\left(m_\ell^4/q^4\right) + \mathcal{O}\left(\alpha_e\right)$ [CB/Hiller/Piranishvili 0709.4174]
- estimating QED $R_M^{\mu/e}[1,6] = 1.00 \pm 0.01 \quad (H = K, K^*)$ [Bordone/Isidori/Pattori 1605.07633]

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[Hiller/Krüger hep-ph/0310219]

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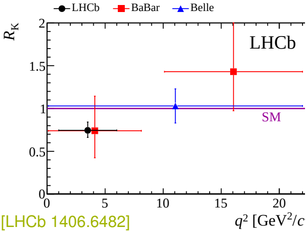
Measurement $R_K^{\mu/e}$

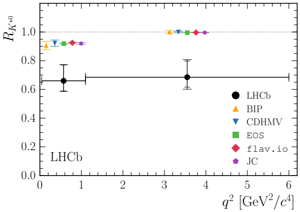


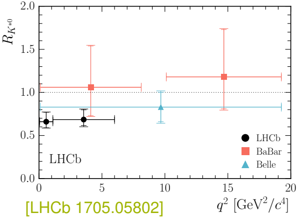
[LHCb 1406.6482]

$$R_K^{\mu/e}[1,6] = 0.745^{+0.090}_{-0.074} \pm 0.036$$

correponds to tension $2.6\,\sigma$

Measurement $R_{K*}^{\mu/e}$ [Babar 1204.3933, Belle 0904.0770]





[LHCb 1705.05802]

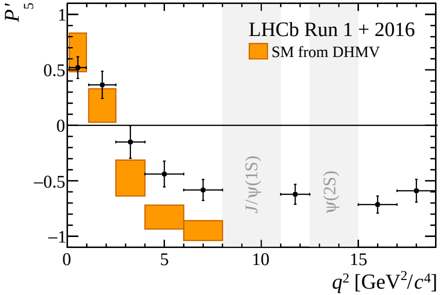
$$R_{K*}^{\mu/e}[0.045, 1.1] = 0.66^{+0.11}_{-0.07} \pm 0.03 \qquad 2.2\,\sigma$$

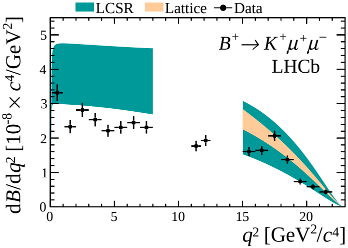
$$R_{K*}^{\mu/e}[1.1, 6.0] = 0.69^{+0.11}_{-0.07} \pm 0.05 \qquad 2.4\,\sigma$$

Tensions in angular distribution $B \to K^* \mu\bar{\mu}$ and rates

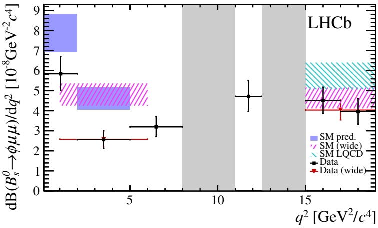
- latest LHCb: Run 1 + 2016
  [LHCb 2003.04831, Belle 1612.05014]
- tensions in bins $q^2 \in [4,6], [6,8]\,\text{GeV}^2$ of about $2.5\,\sigma$ and $2.9\,\sigma$
- bin $q^2 \in [6,8]\,\text{GeV}^2$ hadronic $c\bar{c}$-contributions might not under control

$$P_5' \equiv \frac{J_5/2}{\sqrt{-J_{2c}J_{2s}}}$$





$\mathcal{B}(B^+ \to K^+\mu\bar{\mu})$ data below SM prediction
[LHCb 1403.8044]



$\mathcal{B}(B_s \to \phi\mu\bar{\mu})$ ($2.2\,\sigma$) data below SM prediction
[LHCb 1506.08777]

$\Rightarrow$ all measured LHCb rates ($\ell = \mu$) systematically below SM predictions

Power corrections for $q^2 \lesssim 6$ GeV^2

Parameterisation hadronic matrix element
$\lambda = \pm, 0$

$h_\lambda^{(i)} \to \sqrt{q^2} h_\lambda^{(i)}$
for $\lambda = 0$

$$\mathcal{H}_\lambda(q^2) = \frac{\epsilon_\mu^*(\lambda)}{m_B^2} \int \mathrm{d}^4x\, e^{i\,q\cdot x} \left\langle K_\lambda^{(*)} \middle| \mathrm{T}\left\{ j_\mu^{\mathrm{em}}(x), \sum_i C_i \mathcal{O}_i(0) \right\} \middle| B(p) \right\rangle$$

$$\approx \underbrace{\left[\text{LO in } 1/m_b\right]}_{\text{QCDF}} + h_\lambda^{(0)} + \frac{q^2}{1\text{GeV}^2} h_\lambda^{(1)} + \frac{q^4}{1\text{GeV}^4} h_\lambda^{(2)}, \qquad h_\lambda^{(0,1,2)} \in \mathbb{C}$$

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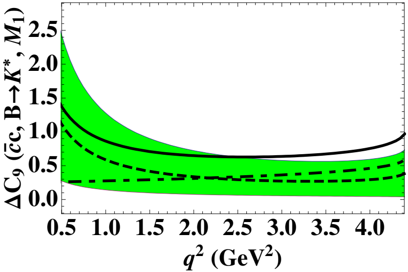
$h_\lambda^{(i)} \to \sqrt{q^2}\, h_\lambda^{(i)}$ for $\lambda = 0$

$\Rightarrow$ Soft-gluon emission off $c\bar{c}$-pairs calculated in light-cone OPE

[Khodjamirian et al. 1006.4945 + 1211.0234 + 1506.07760]



1) Leading contribution
   $\Rightarrow$ previously known QCDF result

2) contributions to $\mathcal{H}_\lambda(q^2)$ via OPE

- works for $\Lambda_{\text{QCD}} \ll 4m_c^2 - q^2$, also at $q^2 < 0$ GeV^2
- gives q^2-dependent shift to C_9
  $\Delta C_9^1(q^2) = (C_1 + 3C_2) g_{\text{fact}}(q^2) + 2C_1 \tilde{g}_1(q^2)$
  with $\tilde{g}_1(q^2) \propto h_-(q^2) - h_+(q^2)$
- $g_{\text{fact}}(q^2)$ = LO in $1/m_b$ = *dashed*
- soft-gluon emission $\tilde{g}_1(q^2)$ = *dashed-dotted*

$\Rightarrow$ power corrections from soft gluons about 10–20% of C_9 at $1.0 \le q^2 \le 4.0$ GeV^2

3) interpolation up to $q^2 \approx 12$ GeV^2 via dispersion relation

Power corrections for $q^2 \lesssim 6$ GeV^2

Parameterisation hadronic matrix element $\lambda = \pm, 0$

$$\mathcal{H}_\lambda(q^2) = \frac{\epsilon^*_\mu(\lambda)}{m_B^2} \int d^4x\, e^{i q\cdot x} \left\langle K_\lambda^{(*)} \middle| T\left\{ j_\mu^{\rm em}(x), \sum_i C_i \mathcal{O}_i(0) \right\} \middle| B(p) \right\rangle$$

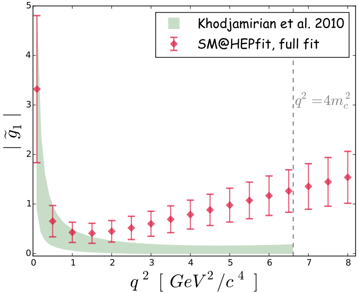
$$\approx \underbrace{[\text{LO in } 1/m_b]}_{\text{QCDF}} + h_\lambda^{(0)} + \frac{q^2}{1\text{GeV}^2} h_\lambda^{(1)} + \frac{q^4}{1\text{GeV}^4} h_\lambda^{(2)}, \qquad h_\lambda^{(0,1,2)} \in \mathbb{C}$$

$h_\lambda^{(i)} \to \sqrt{q^2}\, h_\lambda^{(i)}$ for $\lambda = 0$

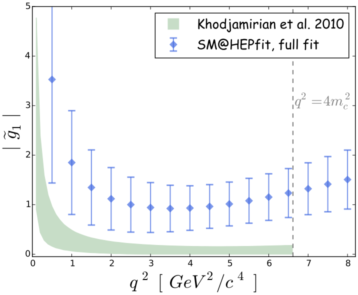
In absence of 1st-principle calculation of $h_\lambda^{(i)}$ can not distinguish $h_\lambda^{(0)} \leftrightarrow C_7^{\rm NP}$ and $h_\lambda^{(1)} \leftrightarrow C_9^{\rm NP}$

$\Rightarrow$ Can fit $h_\lambda^{(0,1,2)}$ from data (assuming $C_9^{\rm NP} = 0$) [Ciuchini et al. 1512.07157]

with OPE-result at $q^2 = 0, 1$ GeV^2



without OPE-result



$\Rightarrow$ leads $(5-10)\times$ larger power corrections than predicted by Khodjamirian et al. for $\tilde{g}$'s

Power corrections for $q^2 \lesssim 6$ GeV^2

Parameterisation hadronic matrix element $\lambda = \pm, 0$

$h_\lambda^{(i)} \to \sqrt{q^2} h_\lambda^{(i)}$ for $\lambda = 0$

$$\mathcal{H}_\lambda(q^2) = \frac{\epsilon_\mu^*(\lambda)}{m_B^2} \int d^4x\, e^{i q\cdot x} \left\langle K_\lambda^{(*)} \middle| T\left\{ j_\mu^{\rm em}(x), \sum_i C_i \mathcal{O}_i(0) \right\} \middle| B(p) \right\rangle$$

$$\approx \underbrace{\left[\text{LO in } 1/m_b\right]}_{\text{QCDF}} + h_\lambda^{(0)} + \frac{q^2}{1\text{GeV}^2} h_\lambda^{(1)} + \frac{q^4}{1\text{GeV}^4} h_\lambda^{(2)}, \qquad h_\lambda^{(0,1,2)} \in \mathbb{C}$$

- **In global fits:** magnitude of power corrections taken from KMPW'10 = Khodjamirian/Mannel/Pivovarov/Wang 1006.4945

  BUT allowing for both signs

- sign of power corrections predicted by KMPW'10 increases NP contribution to C_9

- large power corrections can not explain $R_{K,K^*}^{\mu/e}$ measurement, but it can not be excluded that they origin of P_5' and low $\mathcal{B}$'s

$R_K^{\mu/e}$ and $R_{K^*}^{\mu/e}$ – What type of operators?

- dipole and four-quark op's can not induce $R_H \neq 1$
- scalar op's: strongly disfavored [Hiller/Schmaltz 1408.1627]
- tensor op's: only for $\ell = e$, but require interference with other op's [Bardhan et al. 1705.09305]

$\Rightarrow$ **vector op's**: $\mathcal{O}^{\ell}_{9(9')} = [\bar{s}\gamma^{\mu} P_{L(R)}\, b][\bar{\ell}\gamma_{\mu}\,\ell]$ and $\mathcal{O}^{\ell}_{10(10')} = [\bar{s}\gamma^{\mu} P_{L(R)}\, b][\bar{\ell}\gamma_{\mu}\gamma_5\,\ell]$

$R_K^{\mu/e}$ and $R_{K^*}^{\mu/e}$ – What type of operators?

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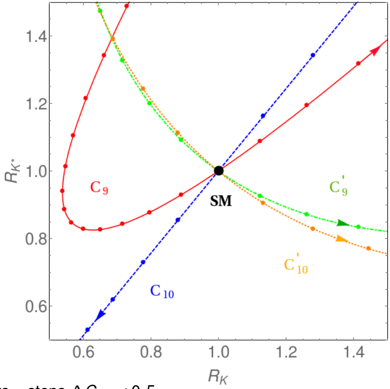
⇒ **vector op's**: $\mathcal{O}^\ell_{9(9')} = [\bar{s}\gamma^\mu P_{L(R)}\, b][\bar{\ell}\gamma_\mu\, \ell]$ and $\mathcal{O}^\ell_{10(10')} = [\bar{s}\gamma^\mu P_{L(R)}\, b][\bar{\ell}\gamma_\mu\gamma_5\, \ell]$

modifications of $C^\mu_{9,9',10,10'}$ **and/or** $C^e_{9,9',10,10'}$

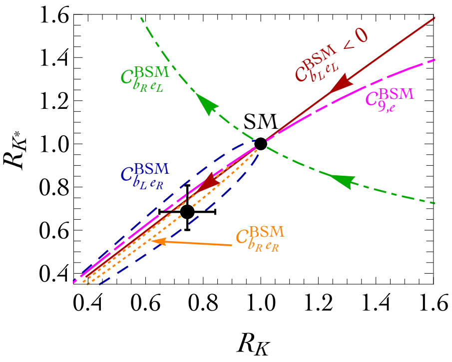
[Geng et al. 1704.05446]



points = steps $\Delta C_i = \pm 0.5$

[D'Amico et al. 1704.05438]

New physics in e



arrow = step $\Delta C_i = \pm 1.0$

Fits of Wilson coefficients

Fit $b \to s\ell\bar{\ell}$ ($\ell = e, \mu$) for single C_i^ℓ at $\mu \sim m_b$

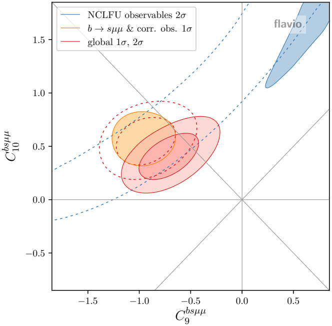
- in SM $C_9^{\mathrm{SM}} \simeq 4.2$ and $C_{10}^{\mathrm{SM}} \simeq -4.3$
- chirality-flipped C_i' disfavored
- preference for $\ell = \mu$ over $\ell = e$
- best single-WC scenario $C_9^\mu = -C_{10}^\mu$

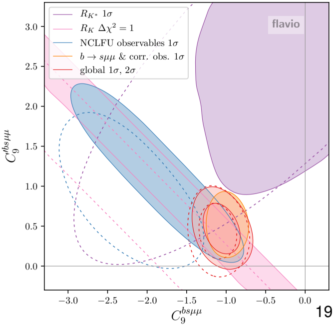
[Aebischer et al. 1903.10434]

Coeff.	best fit	1σ	pull
C_9^μ	-0.97	$[-1.12, -0.81]$	5.9σ
C_{10}^μ	$+0.75$	$[+0.62, +0.89]$	5.7σ
C_9^e	$+0.93$	$[+0.66, +1.17]$	3.5σ
C_{10}^e	-0.83	$[-1.05, -0.60]$	3.6σ
$C_9^\mu = -C_{10}^\mu$	-0.53	$[-0.61, -0.45]$	6.6σ
$C_9^e = -C_{10}^e$	$+0.47$	$[+0.33, +0.59]$	3.5σ
$C_9'^\mu$	$+0.14$	$[-0.03, +0.32]$	0.8σ
$C_{10}'^\mu$	-0.24	$[-0.36, +0.12]$	2.0σ
$C_9'^e$	$+0.39$	$[-0.05, +0.65]$	1.2σ
$C_{10}'^e$	-0.27	$[-0.57, -0.02]$	1.1σ

pull = $\sqrt{\chi^2_{\mathrm{SM}} - \chi^2_{\mathrm{b.f.}}}$ in 1-dim

[see also 1903.09578, 1903.09632, 1903.09617, 2006.04213]





Assume lepton-flavor universal contributions

Can also assume that some part is lepton-flavor universal among all Wilson coefficients

$$C_i^\ell = C_i^{\text{univ}} + \Delta C_i^\ell$$

⇒ LFU-part arises for example from RG effects in SMEFT etc.

Example with 2 parameters C_9^{univ} and ΔC^μ

$$C_9^\mu = C_9^{\text{univ}} + \Delta C^\mu$$

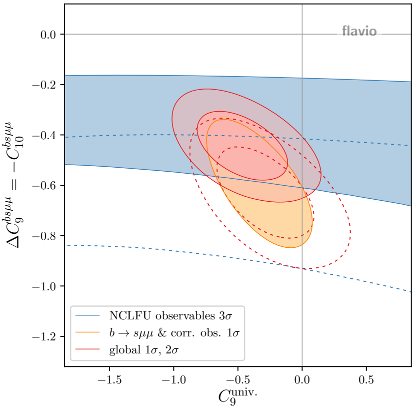
$$C_9^e = C_9^\tau = C_9^{\text{univ}}$$

$$C_{10}^\mu = -\Delta C^\mu$$

$$C_{10}^e = C_{10}^\tau = 0$$

(i.e. $\Delta C_{10}^{\text{univ}} = 0$)

[Aebischer et al. 1903.10434]



[solid] Moriond 2019

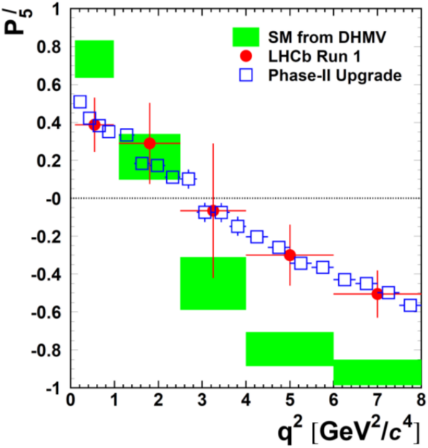
[dashed] pre-Moriond 2019

Prospects $b \to s\ell\bar{\ell}$

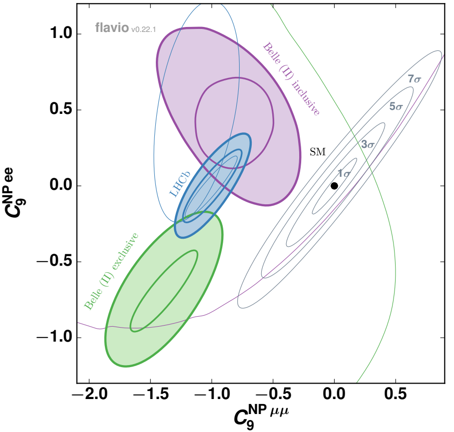
If LFU anomalies persit then LHCb

- $R_K^{\mu/e}$ with $> 5\,\sigma$ Run II (2018) and $> 15\,\sigma$ Run IV (2030)
- $R_{K^*}^{\mu/e}$ with $> 3\,\sigma$ Run II (2018) and $> 6\,\sigma$ Run III (2023) and $> 10\,\sigma$ Run IV (2030)

Belle II will confirm $R_{K,K^*}^{\mu/e}$ with $7-8\,\sigma$ with 50/ab



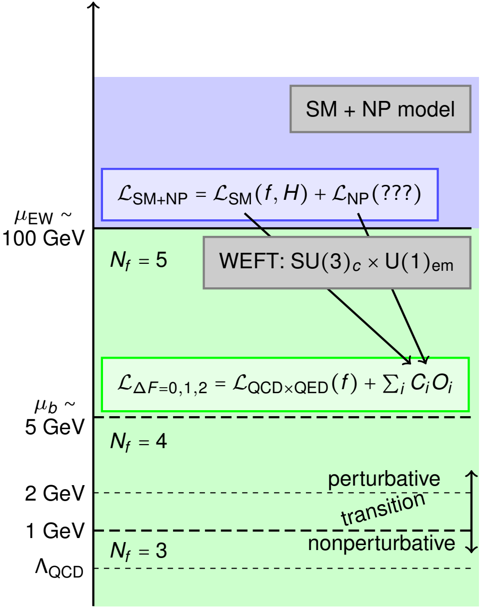
[LHCb CERN-LHCC-2017-003]



current avg = not filled, benchm. pnt's = filled,
SM excl. contours with LHCb 50/fb + Belle II 50/ab
[Albrecht/Bernlochner/Kenzie/Reichert/Straub/Tully 1709.10308]

New Physics interpretation

Factorization via stack of effective theories (EFT)

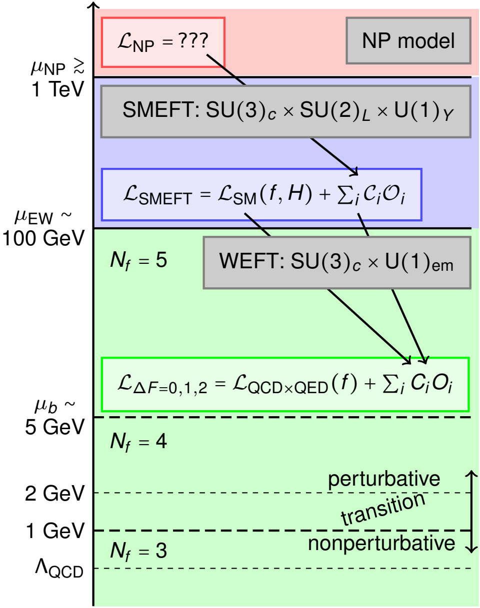


- decoupling of SM and potential NP at electroweak scale μ_{EW}
- assumes no other (relevant) light particles below μ_{EW} (some Z', ...)

WEFT (weak EFT)

- # of op's [Jenkins/Manohar/Stoffer 1709.04486]
  ($L + B$ conserving) dim-5: 70, dim-6: 3631
- **perturbative part** → in SM under control
  - ⇒ decoupling @ NNLO QCD + NLO EW
  - ⇒ RGE @ NNLO QCD + NLO QED
- **hadronic matrix elements**
  - ⇒ ***B*-physics**
    - $1/m_b$ exp's → universal hadr. objects
    - Lattice
    - light-cone sum rules (LCSR)
  - ⇒ ***K*-physics**
    - Lattice
    - χ-PT LEC

Factorization via stack of effective theories (EFT)



SMEFT (SM EFT)

- assume mass gap $\mu_{\rm EW} \ll \mu_{\rm NP}$
  (not yet experimentally justified)
- parametrize NP effects by dim-5 + 6 op's
  \# of op's (*L* + *B* conserving)
  dim-5: 1, dim-6: 2499
- 1-loop RGE [Alonso/Jenkins/Manohar/Trott 1312.2014]

WEFT (weak EFT)

- \# of op's [Jenkins/Manohar/Stoffer 1709.04486]
  (*L* + *B* conserving) dim-5: 70, dim-6: 3631
- **perturbative part** → in SM under control
  ⇒ decoupling @ NNLO QCD + NLO EW
  ⇒ RGE @ NNLO QCD + NLO QED
- **hadronic matrix elements**
  ⇒ ***B*-physics**
  - $1/m_b$ exp's → universal hadr. objects
  - Lattice
  - light-cone sum rules (LCSR)

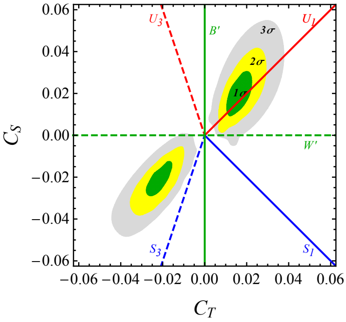
  ⇒ ***K*-physics**
  - Lattice
  - χ-PT LEC

NP models

"Grand-scheme" models (MSSM etc.) usually predict $C_9 \ll C_{10}$ (modified Z-penguin)

$\Rightarrow$ contradict global fits $C_9 \sim -C_{10}$

"Simplified" models in B-physics: massive bosonic mediators at $\mu_{\rm NP} \sim \mathcal{O}(\text{TeV})$



[Buttazzo/Greljo/Isidori/Marzocca 1706.07808]

Colorless $S = 1$:	$B' = (1,1,0)$, $W' = (1,3,0)$
LQ's (LeptoQuarks) $S = 0$:	$S_1 = (\overline{3},1,1/3)$, $S_3 = (\overline{3},3,1/3)$
LQ's $S = 1$:	$U_1 = (3,1,2/3)$, $U_3 = (3,3,2/3)$

$\Rightarrow$ U_1 most promising single-mediator scenario

$\Rightarrow$ combinations of several LQs (also other rep's)

!!! single-mediator B', W' problems with B_s-mix & high-p_T

UV completions for

- extended gauge & Higgs sectors
- LQ's: weakly interacting (elementary scalar or gauge boson)
- LQ's: strongly interacting (scalar as LQ as GB, composite vector LQ)

$\Rightarrow$ rather difficult to build explicit viable models

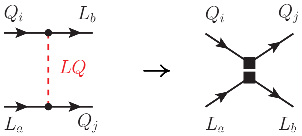
LeptoQuarks and $b \to s\ell\bar{\ell}$: "EW gauge mixing"

Assumption of hierarchy $\mu_\Lambda \approx M_{LQ} > \mathcal{O}(\text{TeV}) \gg \mu_{ew} \approx 100\,\text{GeV}$

- at μ_Λ: LQ decpl = **match on SMEFT** (Standard Model EFT)

  $\Rightarrow$ at tree-level → only SL-ψ^4 op's (semi-leptonic)

  $\propto (\bar{Q}_j \Gamma Q_i)(\bar{L}_a \Gamma L_b)$



LeptoQuarks and $b \to s\ell\bar{\ell}$: "EW gauge mixing"

Assumption of hierarchy $\quad \boxed{\mu_\Lambda \approx M_{LQ} > \mathcal{O}(\text{TeV}) \quad \gg \quad \mu_{ew} \approx 100\,\text{GeV}}$

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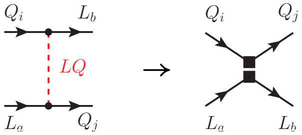
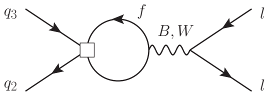


- from $\mu_\Lambda \to \mu_{ew}$: **SMEFT RG evolution** (renormalization group)

  $\Rightarrow$ mixing into SL-ψ^4 op's $\propto (\bar{Q}_j \Gamma Q_i)(\bar{L}_{a'} \Gamma L_{b'})$

  $\Rightarrow$ large log's $\ln \mu_\Lambda / \mu_{ew}$ [Alonso/Jenkins/Manohar/Trott 1312.2014]

$$\mathcal{C}_{SL-\psi^4}(\mu_{ew}) = \frac{\gamma_{SL,SL}}{(4\pi)^2} \ln \frac{\mu_\Lambda}{\mu_{ew}} \mathcal{C}_{SL-\psi^4}(\mu_\Lambda)$$



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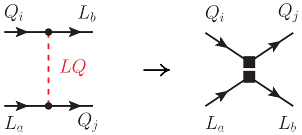

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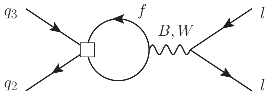
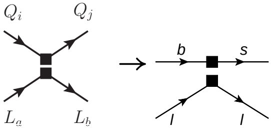


- at μ_{ew}: **matching of SMEFT on $\mathcal{L}_{\Delta B=1}$** for $b \to s\ell\bar{\ell}$

  in terms of $\Delta B = 1$ operators

$$Q^{\ell}_{9(9')} = [\bar{s}\gamma^\mu P_{L(R)} b][\bar{\ell}\gamma_\mu \ell]$$

$$Q^{\ell}_{10(10')} = [\bar{s}\gamma^\mu P_{L(R)} b][\bar{\ell}\gamma_\mu \gamma_5 \ell]$$



Interpretation within SMEFT

Matching SMEFT on $b \to s\ell\bar{\ell}$ at tree-level at μ_{ew}

$$
\begin{aligned}
C_9^\ell &\propto \left[\mathcal{C}_{qe}\right]_{23\ell\ell} + \left[\mathcal{C}_{lq}^{(1)}\right]_{\ell\ell 23} + \left[\mathcal{C}_{lq}^{(3)}\right]_{\ell\ell 23} - (1 - 4s_W^2)\left(\left[\mathcal{C}_{Hq}^{(1)}\right]_{23} + \left[\mathcal{C}_{Hq}^{(3)}\right]_{23}\right) \\
C_{10}^\ell &\propto \left[\mathcal{C}_{qe}\right]_{23\ell\ell} - \left[\mathcal{C}_{lq}^{(1)}\right]_{\ell\ell 23} - \left[\mathcal{C}_{lq}^{(3)}\right]_{\ell\ell 23} + \left(\left[\mathcal{C}_{Hq}^{(1)}\right]_{23} + \left[\mathcal{C}_{Hq}^{(3)}\right]_{23}\right) \\
C_{9'}^\ell &\propto \left[\mathcal{C}_{ed}\right]_{\ell\ell 23} + \left[\mathcal{C}_{ld}\right]_{\ell\ell 23} - (1 - 4s_W^2)\left[\mathcal{C}_{Hd}\right]_{23} \\
C_{10'}^\ell &\propto \left[\mathcal{C}_{ed}\right]_{\ell\ell 23} + \left[\mathcal{C}_{ld}\right]_{\ell\ell 23} - \left[\mathcal{C}_{Hd}\right]_{23}
\end{aligned}
$$

- $C_{9,10}$ depend on 5 Wilson coefficients
- $C_{9',10'}$ depend on 3 Wilson coefficients
- modified Z-coupl's $\mathcal{C}_{Hq}^{(1,3)}$ and $\mathcal{C}_{Hd}$ suppressed in $C_{9,9'}$ by $(1 - s_W^2) \sim 0.08$ w.r.t. $C_{10,10'}$
- $C_{V_L} \propto \mathcal{C}_{lq}^{(3)}$ enters also $b \to c\tau\nu$

SMEFT operators: Semileptonic ψ^4 and modified $Z, W^\pm$-couplings $\psi^2 H^2 D$

$$
\mathcal{O}_{lq}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t) \qquad \mathcal{O}_{lq}^{(3)} = (\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)
$$

$$
\mathcal{O}_{qe} = (\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t) \qquad \mathcal{O}_{ld} = (\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t) \qquad \mathcal{O}_{ed} = (\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)
$$

$$
\mathcal{O}_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{\mathcal{D}}_\mu H)[\bar{q}_L^i\gamma^\mu q_L^j], \quad \mathcal{O}_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{\mathcal{D}}_\mu^a H)[\bar{q}_L^i\sigma^a\gamma^\mu q_L^j] \quad \mathcal{O}_{Hd} = (H^\dagger i\overleftrightarrow{\mathcal{D}}_\mu H)[\bar{d}_R^i\gamma^\mu d_R^j]
$$

Interlude on SMEFT operators

Consider SMEFT operators, ***ijmn* = generation indices**

$$[\mathcal{O}_{lq}^{(1)}]_{ijmn} = (\bar{l}_i \gamma_\mu l_j)(\bar{q}_m \gamma^\mu q_n) \qquad [\mathcal{O}_{lq}^{(3)}]_{ijmn} = (\bar{l}_i \gamma_\mu \tau^a l_j)(\bar{q}_m \gamma^\mu \tau^a q_n)$$

these operator are made of $SU(2)_L$ doublets

$$q_i = Q_{L,i} = \begin{pmatrix} u_{L,i} \\ d_{L,i} \end{pmatrix} \qquad l_i = L_{L,i} = \begin{pmatrix} \nu_{L,i} \\ e_{L,i} \end{pmatrix}$$

If we do expansion in $SU(2)_L$ components (τ^a = Pauli matrices, summation over a)

$$\begin{aligned}
[\mathcal{C}_1]_{ijmn}[\mathcal{O}_{lq}^{(1)}]_{ijmn} \; + \; [\mathcal{C}_3]_{ijmn}[\mathcal{O}_{lq}^{(3)}]_{ijmn} \\
&= \Big[(\mathcal{C}_1 + \mathcal{C}_3)_{ijmn} \, (\bar{u}_{iL} \gamma^\mu u_{jL})(\bar{\nu}_{mL} \gamma_\mu \nu_{nL}) + (\mathcal{C}_1 - \mathcal{C}_3)_{ijmn} \, (\bar{u}_{iL} \gamma^\mu u_{jL})(\bar{\ell}_{mL} \gamma_\mu \ell_{nL}) \Big] \\
&+ \Big[(\mathcal{C}_1 - \mathcal{C}_3)_{ijmn} \, (\bar{d}_{iL} \gamma^\mu d_{jL})(\bar{\nu}_{mL} \gamma_\mu \nu_{nL}) + (\mathcal{C}_1 + \mathcal{C}_3)_{ijmn} \, (\bar{d}_{iL} \gamma^\mu d_{jL})(\bar{\ell}_{mL} \gamma_\mu \ell_{nL}) \Big] \\
&+ 2[\mathcal{C}_3]_{ijmn} \Big[(\bar{u}_{iL} \gamma^\mu d_{jL})(\bar{\ell}_{mL} \gamma_\mu \nu_{nL}) + \text{h.c.} \Big]
\end{aligned}$$

← CC's ↑ FCNC's

Still need to rotate flavor → mass basis: $u_L \to V_u u_L, \quad d_L \to V_d d_L, \quad \nu_L \to U_e \nu_L, \quad \ell_L \to U_e \ell_L$

Contribute to all semileptonic CC and FCNC processes!

Fit in SMEFT

Scenario with two parameters at $\mu_\Lambda = 2\,\text{TeV}$:

$$[\mathcal{C}_{lq}^{(1)}]_{3323} = [\mathcal{C}_{lq}^{(3)}]_{3323} \quad \leftarrow \ell = 3 = \tau$$

$$[\mathcal{C}_{lq}^{(1)}]_{2223} = [\mathcal{C}_{lq}^{(3)}]_{2223} \quad \leftarrow \ell = 2 = \mu$$

If there was no mixing from $\mu_\Lambda \to \mu_{ew}$, would expect at μ_{ew}

$$C_9^\mu \propto +[\mathcal{C}_{lq}^{(1)}]_{2223} + [\mathcal{C}_{lq}^{(3)}]_{2223}$$

$$C_{10}^\mu \propto -[\mathcal{C}_{lq}^{(1)}]_{2223} - [\mathcal{C}_{lq}^{(3)}]_{2223}$$

$$C_{V_L}^\tau \propto \sum_x V_{2x}[\mathcal{C}_{lq}^{(3)}]_{33x3}$$

The mixing in SMEFT from semi-tauonic → semi-muonic, provides a C_9^{univ}

BFP

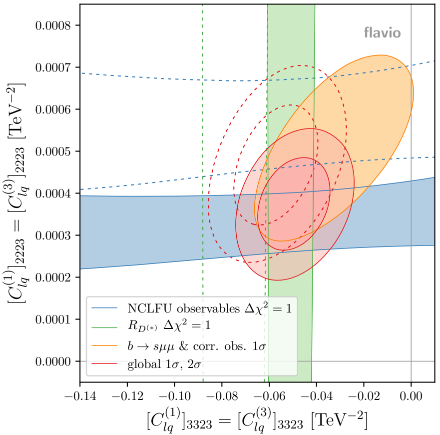
$$[\mathcal{C}_{lq}^{(1)}]_{3323} = -5.0 \cdot 10^{-2}\,\text{TeV}^{-2}$$

$$[\mathcal{C}_{lq}^{(1)}]_{2223} = +3.9 \cdot 10^{-4}\,\text{TeV}^{-2}$$

pull: $7.8\,\sigma$

no bound from $B \to K^{(*)}\nu\bar{\nu}$, because depends on $\mathcal{C}_{lq}^{(1)} - \mathcal{C}_{lq}^{(3)}$

[Aebischer et al. 1903.10434]



can explain both $b \to c\tau\bar{\nu}$ and $b \to s\ell\bar{\ell}$

Assuming tree-level and (couplings)^2 = 1:

$1/\sqrt{0.05} \approx 4.5\,\text{TeV}$

$1/\sqrt{0.0004} \approx 50\,\text{TeV}$

very different scales for semi-tauonic and semi-muonic operators