Recent developments in rare *b* decays

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Roma 3 Seminar

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Outline

- Motivation for quark flavor physics
- Status of tensions in B decays and interpretation
- QED corrections to $B_s \to \mu\bar{\mu}$ (and $B_u \to \ell\bar{\nu}_\ell$)
- Controlling hadronic corrections to exclusive $b \to s\ell\bar{\ell}$

Motivation for quark flavor physics

Origin of flavor in the SM (Standard Model)

3 generations of quarks and leptons: Q_L^i, L_L^i and u_R^i, d_R^i, e_R^i (with $i = 1, 2, 3$)

$$\mathcal{L}_{\rm SM} = \underbrace{\mathcal{L}_{\rm gauge}}_{\text{flavor sym } G_{\rm flavor}\ (\sim \delta^{ij})} + \sum_{ij} \underbrace{\overline{Q}_L^i Y_U^{ij} \widetilde{H} U_R^j + \overline{Q}_L^i Y_D^{ij} H D_R^j}_{\text{break } G_{\rm flavor}\ (\sim Y^{ij}_{D/U})}$$

$\Uparrow$

- Yukawa couplings $Y_{U,D}$ origin of flavor in the SM (in quark sector)
- $6 \times$ quark masses $\propto vev \times {\rm diag}(Y_{U,D}) \Rightarrow$ very hierarchical
- $4 \times V_{\rm CKM} \Rightarrow$ off-diagonal entries strongly suppressed

$$G_{\rm flavor} = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R} \otimes SU(3)_{L_L} \otimes SU(3)_{E_R} \otimes U(1)_{\rm PQ} \otimes U(1)_Y \otimes G_{\rm SM}$$

SM still invariant under $G_{\rm SM} \equiv U(1)_Y \otimes U(1)_B \otimes U(1)_L$

Origin of flavor in the SM (Standard Model)

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SM still invariant under $G_{\rm SM} \equiv U(1)_Y \otimes U(1)_B \otimes U(1)_L$

$\Rightarrow$ the "only" flavor-changing coupling:

$U_i = \{u, c, t\}$:

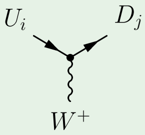
$Q_U = +2/3$

$D_j = \{d, s, b\}$:

$Q_D = -1/3$

$$\mathcal{L}_{\rm CC} = \frac{g_2}{\sqrt{2}} (\bar{u}\ \bar{c}\ \bar{t}) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma^\mu P_L \begin{pmatrix} d \\ s \\ b \end{pmatrix} W^+_\mu$$

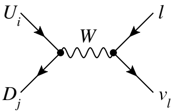
~ Cabibbo-Kobayashi-Maskawa (CKM) matrix



In SM specific pattern of CC and FCNC decays

charged current (CC) $\quad Q_i \neq Q_j$

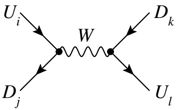
Tree: only $U_i \to D_j$ & $D_i \to U_j$



$M_1 \to \ell\bar{\nu}_\ell$

$M_1 \to M_2 + \ell\bar{\nu}_\ell$

$Amp \sim G_F V_{ij}$

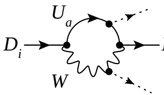


$M_1 \to M_2 M_3$

$\sim G_F V_{ij} V^*_{lk}$

neutral current (FCNC) $\quad Q_i = Q_j$

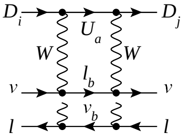
Loop: $D_i \to D_j$ (& $U_i \to U_j$)



$M_1 \to M_2 + \{\gamma, Z, g\}$

$\{\gamma, Z, g\} \to \{\ell\bar{\ell}, \nu\bar{\nu}, M_3\}$

$\sim G_F g \sum_a V_{ai} V^*_{aj} f(m_a)$



$M_1 \to \ell\bar{\ell}$

$M_1 \to M_2 + \{\ell\bar{\ell}, \nu\bar{\nu}, M_3\}$

$M^0 \leftrightarrow \overline{M}^0$ (= mixing)

$\sim G_F g^2 \sum_{a,b} V_{ai} V^*_{aj} f(m_{a,b})$

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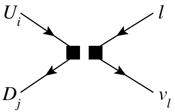
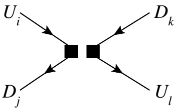
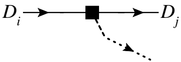
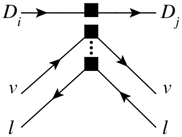








CC (tree)		FCNC (loop)	
$M_1 \to \ell\bar{\nu}_\ell$ $M_1 \to M_2 + \ell\bar{\nu}_\ell$	$M_1 \to M_2 M_3$	$M_1 \to M_2 + \{\gamma, Z, g\}$ $\{\gamma, Z, g\} \to \{\ell\bar{\ell}, \nu\bar{\nu}, M_3\}$	$M_1 \to \ell\bar{\ell}$ $M_1 \to M_2 + \{\ell\bar{\ell}, \nu\bar{\nu}, M_3\}$ $M^0 \leftrightarrow \overline{M}^0$ (= mixing)
$Amp \sim G_F\, C(V_{ij})$	$\sim G_F\, C(V_{ij})$	$\sim G_F\, C(V_{ij}, m_a)$	$\sim G_F\, C(V_{ij}, m_a, m_b)$

- **decoupling for $m_Q \ll m_W \Rightarrow$ effective theory à la Fermi** [Fermi 1934]

  works for all quarks except top quark ($m_W < m_t$)

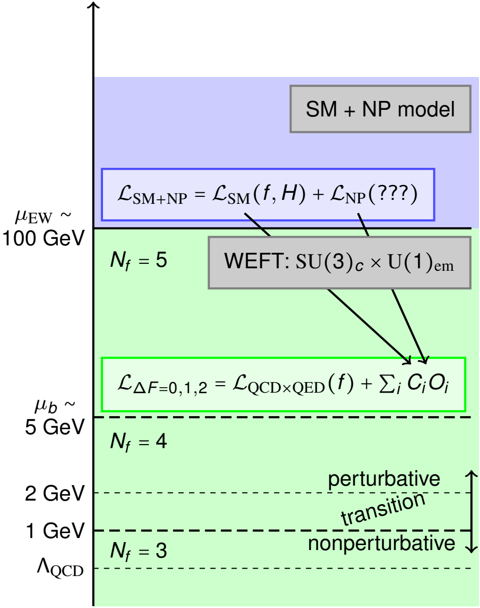
- short-distance (SD) couplings: **C = Wilson coefficients**

  depend on SD-parameters $\Rightarrow$ in SM: CKM and heavy masses: m_W, m_Z, m_t

  $\Rightarrow$ extract in measurement and calculate in specific UV completions

- overall rescaling factor **Fermi's constant $G_F \sim$ GeV^{-2}**, measured in $\mu \to e\bar{\nu}_e\nu_\mu$

Factorization via stack of effective theories (EFT)

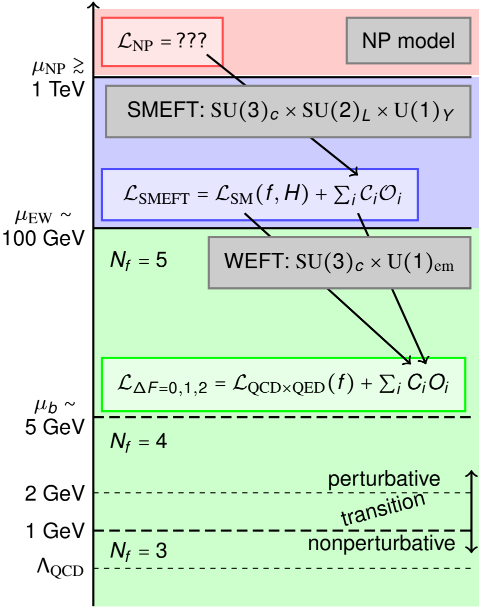


- decoupling of SM and potential NP at electroweak scale $\mu_{\rm EW}$
- assumes no other (relevant) light particles below $\mu_{\rm EW}$ (some Z', ...)

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 (not yet experimentally justified) $\mu_{\rm EW} \ll \mu_{\rm NP}$
- 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)

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

So far "CKM-picture" of SM is confirmed by b-Physics data

⇒ **fit of CKM-Parameters . . .**

[experimental input from CKMfitter homepage]

$\lvert V_{ud}\rvert$ (nuclei)	$0.97425 \pm 0 \pm 0.00022$
$\lvert V_{us}\rvert f_+^{K\to\pi}(0)$	0.2163 ± 0.0005
$\lvert V_{cd}\rvert$ (νN)	0.230 ± 0.011
$\lvert V_{cs}\rvert$ $(W \to c\bar{s})$	$0.94^{+0.32}_{-0.26} \pm 0.13$
$\lvert V_{ub}\rvert$ (semileptonic)	$(4.01 \pm 0.08 \pm 0.22) \times 10^{-3}$
$\lvert V_{cb}\rvert$ (semileptonic)	$(41.00 \pm 0.33 \pm 0.74) \times 10^{-3}$
$\mathcal{B}(\Lambda_p \to p\mu^-\bar{\nu}_\mu)_{q^2>15}/\mathcal{B}(\Lambda_p \to \Lambda_c\mu^-\bar{\nu}_\mu)_{q^2>7}$	$(1.00 \pm 0.09) \times 10^{-2}$
$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau)$	$(1.08 \pm 0.21) \times 10^{-4}$
$\mathcal{B}(D_s^- \to \mu^-\bar{\nu}_\mu)$	$(5.57 \pm 0.24) \times 10^{-3}$
$\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)$	$(5.55 \pm 0.24) \times 10^{-2}$
$\mathcal{B}(D^- \to \mu^-\bar{\nu}_\mu)$	$(3.74 \pm 0.17) \times 10^{-4}$
$\mathcal{B}(K^- \to e^-\bar{\nu}_e)$	$(1.581 \pm 0.008) \times 10^{-5}$
$\mathcal{B}(K^- \to \mu^-\bar{\nu}_\mu)$	0.6355 ± 0.0011
$\mathcal{B}(\tau^- \to K^-\bar{\nu}_\tau)$	$(0.6955 \pm 0.0096) \times 10^{-2}$
$\mathcal{B}(K^- \to \mu^-\bar{\nu}_\mu)/\mathcal{B}(\pi^- \to \mu^-\bar{\nu}_\mu)$	1.3365 ± 0.0032
$\mathcal{B}(\tau^- \to K^-\bar{\nu}_\tau)/\mathcal{B}(\tau^- \to \pi^-\bar{\nu}_\tau)$	$(6.431 \pm 0.094) \times 10^{-2}$
$\mathcal{B}(B_s \to \mu\mu)$	$(2.8^{+0.7}_{-0.6}) \times 10^{-9}$
$\lvert V_{cd}\rvert f_+^{D\to\pi}(0)$	0.148 ± 0.004
$\lvert V_{cs}\rvert f_+^{D\to K}(0)$	0.712 ± 0.007
$\lvert\varepsilon_K\rvert$	$(2.228 \pm 0.011) \times 10^{-3}$
Δm_d	(0.510 ± 0.003) ps^{-1}
Δm_s	(17.757 ± 0.021) ps^{-1}
$\sin(2\beta)_{[c\bar{c}]}$	0.691 ± 0.017
$(\phi_s)_{[b\to c\bar{s}s]}$	-0.015 ± 0.035
$S_{\pi\pi}^{+-}$, $C_{\pi\pi}^{+-}$, $C_{\pi\pi}^{00}$, $\mathcal{B}_{\pi\pi}$ all charges	Inputs to isospin analysis
$S_{\rho\rho,L}^{+-}$, $C_{\rho\rho,L}^{+-}$, $S_{\rho\rho}^{00}$, $C_{\rho\rho}^{00}$, $\mathcal{B}_{\rho\rho,L}$ all charges	Inputs to isospin analysis
$B^0 \to (\rho\pi)^0 \to 3\pi$	Time-dependent Dalitz analysis
$B^- \to D^{(*)}K^{(*)-}$	Inputs to GLW analysis
$B^- \to D^{(*)}K^{(*)-}$	Inputs to ADS analysis
$B^- \to D^{(*)}K^{(*)-}$	GGSZ Dalitz analysis

CKM matrix up to $\mathcal{O}(\lambda^4)$ in terms of
4 Wolfenstein parameters

$$\lambda \sim 0.22, \quad A, \quad \rho, \quad \eta$$

$$V_{ij} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

⇒ nowadays sophisticated fit:

"combine and overconstrain"

!!! numerous b-Physics measurements

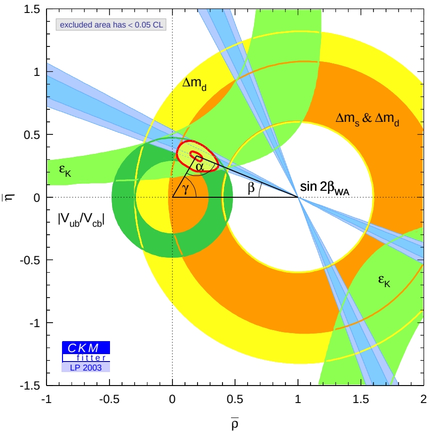
So far “CKM-picture” of SM is confirmed by *b*-Physics data

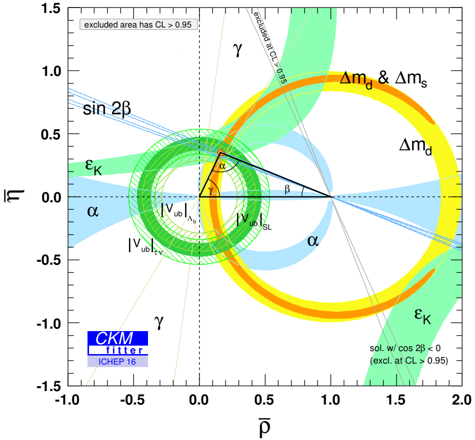
⇒ fit of CKM-Parameters . . . 2003 → 2016 works well

improved by *B*-factories, Tevatron, LHC

CKMfitter results [http://ckmfitter.in2p3.fr/]

Unitarity: $V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0$





See also “UTfit collaboration” [http://www.utfit.org/UTfit/]

See also “SCAN Method” [Eigen et al. arXiv:1301.5867 + 1503.02289]

Timeline of b-physics experiments

LHCb

- Run I: 2010–2012, 3/fb @ 7/8 TeV
- Run II: 2015–2018, 2/fb + 6/fb @ 13 TeV (5× Run I yield)
- Run III: 2021–2023, 30/fb,
  Run IV: 2026–2029, 50/fb, (25×)
- proposed upgrade phase-II, 2031+ 300/fb (200×)

Events in channel	Run I	300/fb
$B_s^0 \to \mu\bar{\mu}$	15	2 700
$B_s^0 \to \mu\bar{\mu}$ (3% tag-power)	—	80
$B^+ \to K^+\mu\bar{\mu}$	4 700	858 500
$B^0 \to K^{*0}\mu\bar{\mu}$	2 400	438 000
$B^+ \to \pi^+\mu\bar{\mu}$	90	16 400
$B^0 \to \rho^0\mu\bar{\mu}$	40	7 300
$B^+ \to K^+ e\bar{e}$ $(q^2 \in [1,6])$	250	91 000
$B^0 \to K^{*0} e\bar{e}$ $(q^2 \in [1,6])$	110	40 200
$B_s^0 \to \phi\gamma$	4 000	743 000
$B_s^0 \to \phi\gamma$ (3% tag-power)	—	22 300

[K. Alvarez Cartelle @ HL-LHC WS, CERN, Oct. 2017]

Belle II

- Comissioning runs late 2018
- Physics run: 2019–2024,
  50/ab = 50× Belle I

Complementary to LHCb for

- absolute branching fraction measurements for normalization
- final states with
  → neutral particles
  → invisibles: $b \to s\nu\bar{\nu}$, etc.
  → with electrons $b \to se\bar{e}$
  → . . .

Example V_{ub}

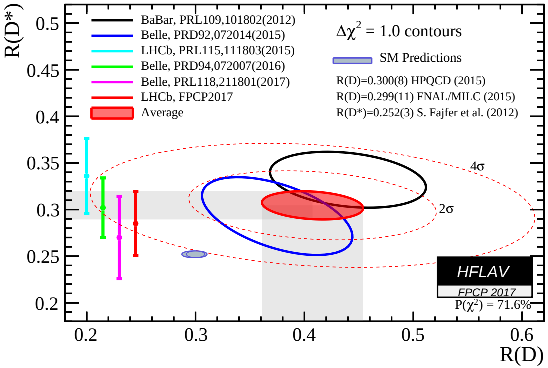
- $B \to \tau\nu$ 3%, $B \to \mu\nu$ 7%

. . . and hadronic parameters

- $B \to \gamma\ell\nu \to$ B-meson DA ($\lambda_{B,+}$, etc.)

Status of tensions in B decays and interpretation

Breaking of LFU at tree-level: $b \to c\ell\bar{\nu}_\ell$



$$R^{\tau/\ell}_{D^{(*)}} \equiv \frac{Br\left[B \to D^{(*)}\tau\bar{\nu}_\tau\right]}{Br\left[B \to D^{(*)}\ell\bar{\nu}_\ell\right]}$$

- **combined deviation $4.1\,\sigma$ from SM**
- single $R(D)$ $2.2\,\sigma$
- single $R(D^*)$ $3.4\,\sigma$
- new measurement $B_c \to J/\psi\tau\bar{\nu}_\tau$ [LHCb 1711.05623]

single $R(J/\psi) \sim 2\,\sigma$

$R(J/\psi) = 0.71 \pm 0.25$

versus

$R(J/\psi)_{\rm SM} = 0.25\ldots0.28$

Additional measurements include

- q^2-diff. distributions [Babar 1303.0571, Belle 1507.03233]
- τ-polarization [Belle 1612.00529]
- bound from B_c-total width [Li/Yang/Zhang 1605.09308]
- inclusive $B \to X_c\tau\nu$ [LEP PDG]

Diagnosing possible NP scenarios

WEFT approach

(assuming no light ν_R)

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

$$\mathcal{L}_{b\to c\tau\nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_{a=1}^{5} C_a \mathcal{O}_a$$

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

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

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

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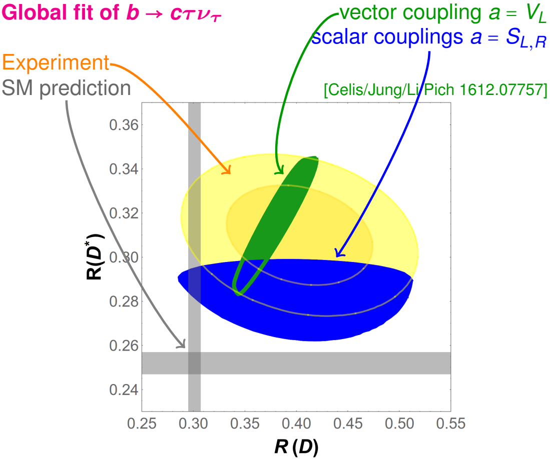
Global fit of $b \to c\tau\nu_\tau$



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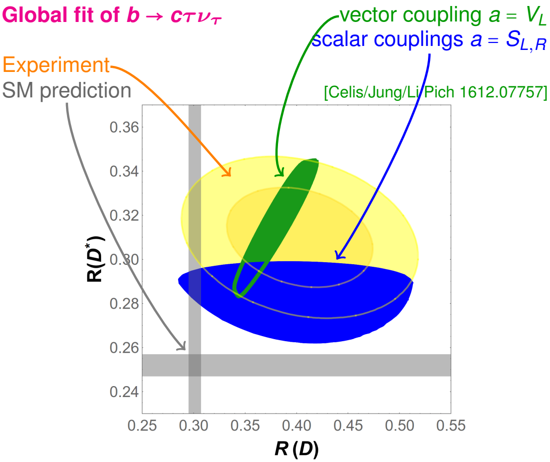
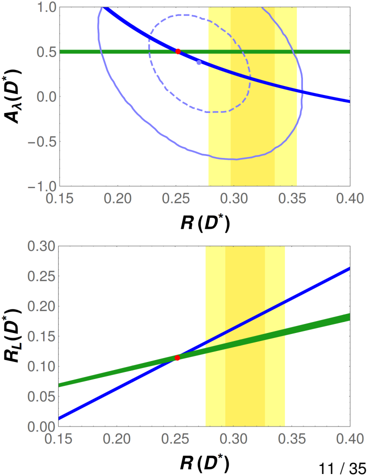


Predictions for $A_\lambda(D^*)$ and R_L



Breaking of LFU at loop-level: $b \to s\ell\bar{\ell}$

$$R_H^{\mu/e} \equiv \frac{Br[B \to H\mu\bar{\mu}]_{[q_a^2, q_b^2]}}{Br[B \to He\bar{e}]_{[q_a^2, q_b^2]}}$$

$H = K, K^*, \phi, X_s, \ldots$

[Hiller/Krüger hep-ph/0310219]

in SM cancellations of

- CKM and hadronic uncertainties
- experimental systematics

- in SM "universality" $R_H^{\mu/e} \approx 1 + \mathcal{O}\left(m_\ell^4/q^4\right) + \mathcal{O}(\alpha_e)$ [CB/Hiller/Piranishvili 0709.4174]

  $m_\ell^2/q^2 < 0.01$ for $q^2 > 1$ GeV^2
- estimating QED $R_H^{\mu/e}[1,6] = 1.00 \pm 0.01 \quad (H = K, K^*)$ [Bordone/Isidori/Pattori 1605.07633]

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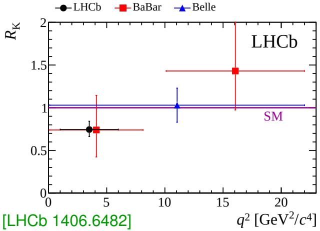
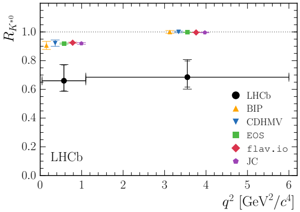
Measurement $R_K^{\mu/e}$

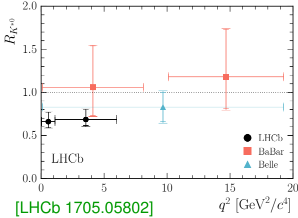


[LHCb 1406.6482]

Measurement $R_{K^*}^{\mu/e}$

[Babar 1204.3933, Belle 0904.0770]





[LHCb 1705.05802]

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

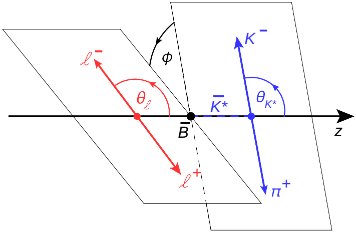
correponds to tension $2.6\,\sigma$

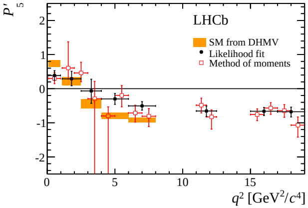
$R_{K^*}^{\mu/e}[0.045, 1.1] = 0.66^{+0.11}_{-0.07} \pm 0.03 \quad 2.2\,\sigma$

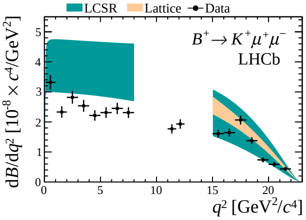
$R_{K^*}^{\mu/e}[1.1, 6.0] = 0.69^{+0.11}_{-0.07} \pm 0.05 \quad 2.4\,\sigma$

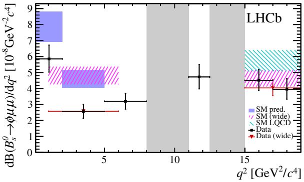
Tensions in angular distribution $B \to K^* \mu\bar{\mu}$ and rates

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









$$P'_5 \equiv \frac{J_5/2}{\sqrt{-J_{2c}J_{2s}}} \qquad 2.9\,\sigma$$

[LHCb 1512.04442, Belle 1612.05014]

$Br(B^+ \to K^+\mu\bar{\mu})$

[LHCb 1403.8044]

data below SM prediction

$Br(B_s \to \phi\mu\bar{\mu}) \quad 2.2\,\sigma$

[LHCb 1506.08777]

data below SM prediction

$R_K^{\mu/e}$ 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]

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

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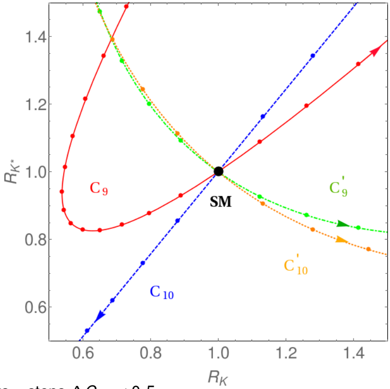
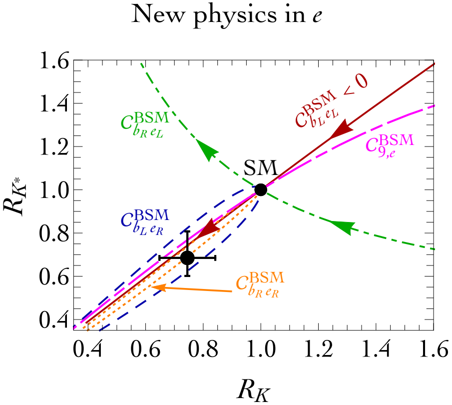
modifications of $\mathcal{C}^{\mu}_{9,9',10,10'}$ **and/or** $\mathcal{C}^{e}_{9,9',10,10'}$

[D'Amico et al. 1704.05438]

[Geng et al. 1704.05446]



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



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

Fits of $R^{\mu/e}_{K,K^*}$ and combination with global $b \to s\mu\bar{\mu}$

Fit R_K and R_{K^*} for various C_i^ℓ,

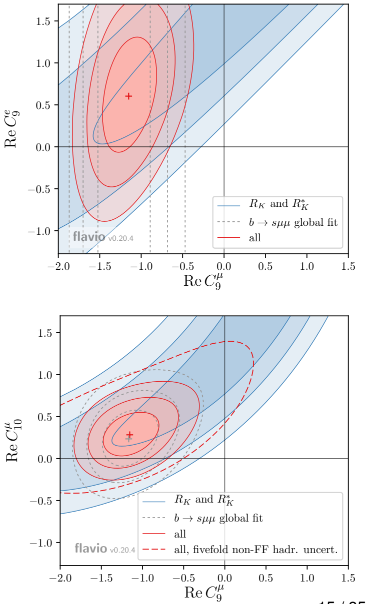
- include $D_{P'_{4,5}}$ measurement [Belle 1612.05014]
- chirality-flipped C_i' disfavored
- no preference of any $\ell = e$ or $\ell = \mu$
- compatible with global $b \to s\mu\bar{\mu}$ anomalies

Coeff.	best fit	1σ	pull
C_9^μ	-1.59	$[-2.15, -1.13]$	4.2σ
C_{10}^μ	$+1.23$	$[+0.90, +1.60]$	4.3σ
C_9^e	$+1.58$	$[+1.17, +2.03]$	4.4σ
C_{10}^e	-1.30	$[-1.68, -0.95]$	4.4σ
$C_9^\mu = -C_{10}^\mu$	-0.64	$[-0.81, -0.48]$	4.2σ
$C_9^e = -C_{10}^e$	$+0.78$	$[+0.56, +1.02]$	4.3σ
$C_9'^{\,\mu}$	-0.00	$[-0.26, +0.25]$	0.0σ
$C_{10}'^{\,\mu}$	$+0.02$	$[-0.22, +0.26]$	0.1σ
$C_9'^{\,e}$	$+0.01$	$[-0.27, +0.31]$	0.0σ
$C_{10}'^{\,e}$	-0.03	$[-0.28, +0.22]$	0.1σ

pull = $\sqrt{\chi^2_{\text{SM}} - \chi^2_{\text{b.f.}}}$ in 1-dim $\chi^2_{\text{SM}} = 24.4$ for 5 d.o.f.

[see also Capdevilla et al. 1704.05340, Ciuchini et al. 1704.05447]

[Altmannshofer/Stangl/Straub 1704.05435]



Interpretation within SMEFT

- global WEFT fits prefer certain op's, which correspond to **op's in SMEFT**

$b \to c\tau\bar{\nu}$	vector op's preferred (but scalar not excluded)	$[\mathcal{O}^{(3)}_{\ell q}]_{klij} = [\bar{\ell}^k_L \gamma_\mu \sigma^a \ell^l_L][\bar{q}^i_L \gamma^\mu \sigma^a q^j_L]$	$\Lambda_{\rm NP} \sim 3$ TeV
$b \to s\ell\bar{\ell}$	left-handed vector op's $O^\ell_{9,10}$ with $\ell = \mu$ sufficient	$[\mathcal{O}^{(1)}_{\ell q}]_{klij} = [\bar{\ell}^k_L \gamma_\mu \ell^l_L][\bar{q}^i_L \gamma^\mu q^j_L]$ and $\mathcal{O}^{(3)}_{\ell q}$ other op's disfavored [Celis et al. 1704.05672]	$\Lambda_{\rm NP} \sim 30$ TeV

- in SMEFT 5 Wilson coefficients (after weak → mass basis) for $b \to c\tau\bar{\nu}$ and $b \to s\mu\bar{\mu}$

$$C_{V_L} \sim \sum_i V_{2i} [\mathcal{C}^{(3)}_{\ell q}]_{33i3} \qquad C^\mu_{9,10} \sim \pm \left[\mathcal{C}^{(3)}_{\ell q} + \mathcal{C}^{(1)}_{\ell q}\right]_{2223}$$

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$b \to s\ell\bar{\ell}$	left-handed vector op's $O_{9,10}^{\ell}$ with $\ell = \mu$ sufficient	$[\mathcal{O}_{\ell q}^{(1)}]_{klij} = [\bar{\ell}_L^k \gamma_\mu \ell_L^l][\bar{q}_L^i \gamma^\mu q_L^j]$ and $\mathcal{O}_{\ell q}^{(3)}$ other op's disfavored [Celis et al. 1704.05672]	$\Lambda_{\rm NP} \sim 30$ TeV

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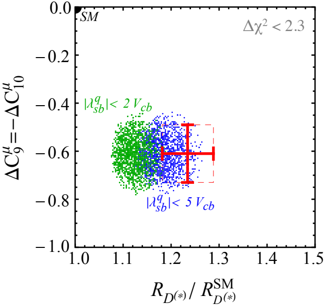
Fit works including

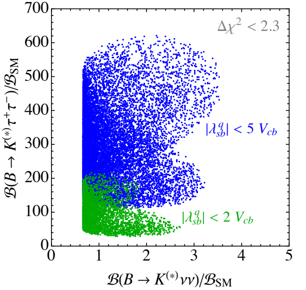
- $R_{D^{(*)}}^{\mu/\tau}$ and $R_{K^{(*)}}^{\mu/e}$
- EWP: Z, W coupl's
- $R_{b\to c}^{\mu/e}$
- $B \to K^{(*)}\nu\bar{\nu}$
- $\tau \to 3\mu$

⇒ compatible with flavor symmetry $U(2)_q \times U(2)_\ell$

⇒ correlation between $Z\tau\bar{\tau}$ & $B \to K^{(*)}\nu\bar{\nu}$

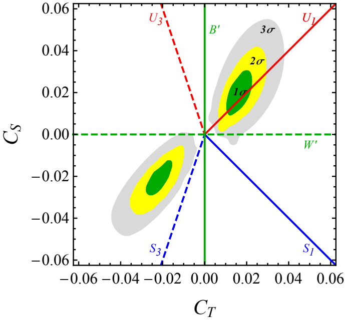
($\mu_{\rm NP} = 2$ TeV) [Buttazzo/Greljo/Isidori/Marzocca 1706.07808]





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) $S = 0$: $S_1 = (\bar{3}, 1, 1/3)$, $S_3 = (\bar{3}, 3, 1/3)$

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

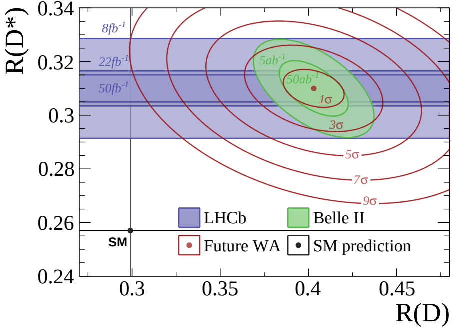
- **UV completions** for
  $\Rightarrow$ extended gauge & Higgs sectors
  $\Rightarrow$ LQ's: weakly interacting (elementary scalar or gauge boson)
  $\Rightarrow$ LQ's: strongly interacting (scalar as LQ as GB, composite vector LQ)

$\Rightarrow$ rather difficult to build explicit viable models [too many to mention]

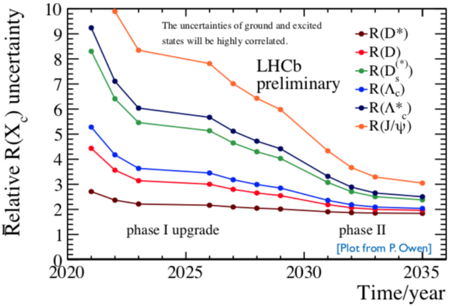
Prospects $b \to c\tau\nu$

[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]



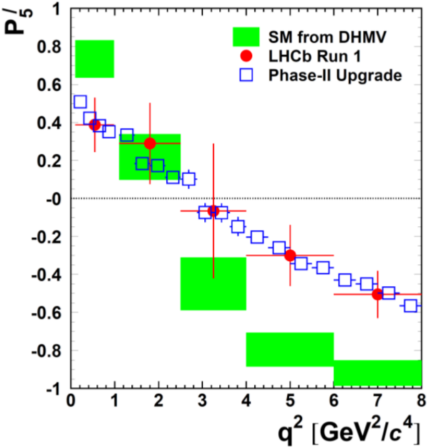
[Patrick Owen @ LHCb Upgrade WS, Elba, 2017]

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

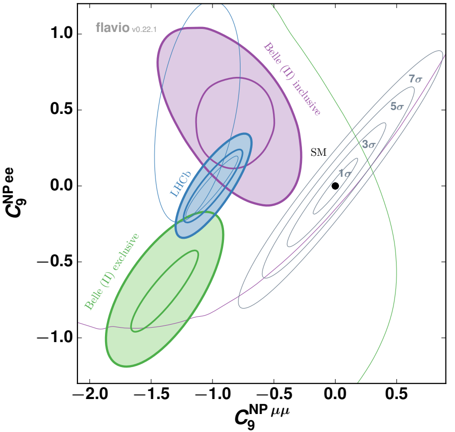
If LFU anomalies persit then LHCb

- $R_K^{\mu/e}$ 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]

QED corrections to

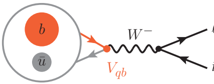
$B_s \to \mu\bar{\mu}$

Martin Beneke, CB and Robert Szafron

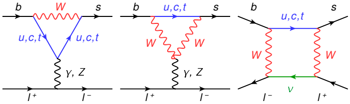
arXiv:1708.09152

Motivation to study $B_q \to \ell\bar{\ell}$ and $B_u \to \ell\bar{\nu}_\ell$

- **Test SM** at tree- (CC) and loop-level (FCNC)



$\propto |V_{ub}|^2$



$\propto |V_{tb} V_{tq}^*|^2$

- **Helicity suppression of SM** $\Rightarrow$ sensitive to NP (pseudo-) scalar interactions

- **Hadronic uncertainty** from decay constant f_{B_q} (at LO in QED)

  $\Rightarrow$ from lattice in future $\delta f_{B_q} \lesssim 0.5\%$

  $f_{B_u} = (189.4 \pm 1.4)$ MeV $\quad f_{B_s} = (230.7 \pm 1.2)$ MeV [FNAL/MILC 1712.09262]

  $\Rightarrow$ theoretical control of $\delta Br \sim 1\%$ possible

  !!! only other compareable precision in flavor: $Br(K^+ \to \pi^+ \nu\bar{\nu})$ (NA62), $Br(K_L \to \pi^0 \nu\bar{\nu})$ (KOTO), $\Delta M_{d,s}$ (lattice)

- **Experimental measurement**

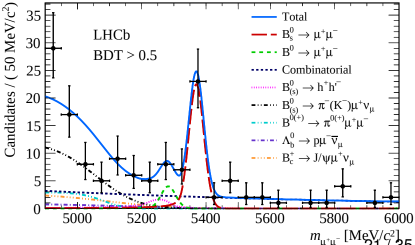
$$\overline{Br}(B_s \to \mu\bar{\mu}) = (3.0 \pm 0.5) \times 10^{-9}$$

$$\overline{Br}(B_d \to \mu\bar{\mu}) < 3.4 \times 10^{-10} \text{ @ } 95\%$$

$$\mathcal{A}_{\Delta\Gamma}(B_s \to \mu\bar{\mu}) = 8.24 \pm 10.72$$

[CMS 1307.5025, LHCb 1307.5024, 1703.05747]

LHCb → mass-eigenstate rate asymmetry



Analysing NP in $B_s \to \mu\bar{\mu}$ via time-dependence

3 CP asymmetries $|C^\lambda|^2 + |S^\lambda|^2 + |A^\lambda_{\Delta\Gamma}|^2 = 1$

$$\frac{\Gamma(B_s(t) \to \mu_\lambda\bar{\mu}_\lambda) - \Gamma(\overline{B}_s(t) \to \mu_\lambda\bar{\mu}_\lambda)}{\Gamma(B_s(t) \to \mu_\lambda\bar{\mu}_\lambda) + \Gamma(\overline{B}_s(t) \to \mu_\lambda\bar{\mu}_\lambda)} = \frac{C^\lambda \cos(\Delta M_s t) + S^\lambda \sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s}) + A^\lambda_{\Delta\Gamma} \sinh(y_s t/\tau_{B_s})}$$

- $A_{\Delta\Gamma}$ without flavor tagging, S requires flavor-tagging, C^λ requires helicity of leptons
- in **SM "clean" observables**: $A_{\Delta\Gamma} = 1$ $S = 0$ $C^\lambda = 0$
  QED corr's negligible [Beneke/CB/Szafron 1708.09152]
- $(C_{10} - C_{10'})$ helicity suppressed $\Rightarrow$ enhanced sensitivity to $(C_{S(P)} - C_{S'(P')})$

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Distinguishing NP [Fleischer/Galarraga Espinosa/Jaarsma/Tetlalmatzi-Xolocotzi 1709.04735]

- even measurement of $\mathrm{sgn}(C^\lambda)$ can reduce degeneracy

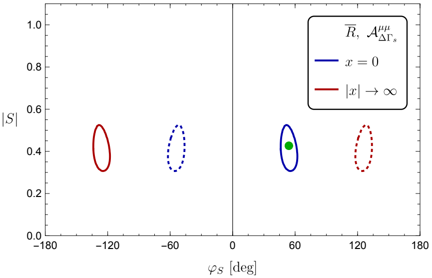
  Benchmark measurement

  $A_{\Delta\Gamma} = +0.58 \pm 0.20$
  $S = -0.80 \pm 0.20$

  $\to$ 4 solutions from Br and $A_{\Delta\Gamma}$

  dashed: ruled out by S

  blue: ruled out by $\mathrm{sgn}C^\lambda$



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Experimental prospects

- for $B_s \to \mu\bar{\mu}$
  @ CMS with 100 fb^{-1} : $\delta(Br) \sim 15\%$ error of SM [Kai-Feng Chen, KEK Flavor Factory WS, 2014]
  @ LHCb with 50 fb^{-1} : $\sigma(Br) \sim 0.15 \times 10^{-9}$ ($\approx 4\%$ of SM) (only stat. err) [LHCb arXiv:1208.3355]
  @ LHCb with 300 fb^{-1} : $\sigma(Br) \sim 0.16 \times 10^{-9}$ ($\approx 4\%$ of SM)
  (with current syst. err = f_s/f_d (5.8%) and norm. mode (3%))
  $\sigma(Br) \sim 0.13 \times 10^{-9}$ ($\lesssim 4\%$ of SM)
  (with 3 % syst. err) [A. Puig @ LHCb Upgrade WS, LAPP, Annecy, 03/2018]
  $\delta(\tau_{\rm eff}) \sim 2\%$, $\sigma(S) \sim 0.2$
- for $B_d \to \mu\bar{\mu}$ $\delta(R_{d/s}) \sim 10\%$ $R_{d/s} \equiv Br(B_d \to \mu\bar{\mu})/Br(B_s \to \mu\bar{\mu})$

Previous SM prediction

- at μ_0: NLO EW + NNLO QCD [CB/Gorbahn/Stamou 1311.1348, Hermann/Misiak/Steinhauser 1311.1347]
- RGE $\mu_0 \to \mu_b$: NLO QED + NNLO QCD

$$\overline{Br}(B_s \to \mu\bar{\mu})_{\rm SM} = (3.65 \pm 0.23) \times 10^{-9} \xrightarrow{\text{update 2017}} = (3.59 \pm 0.17) \times 10^{-9}$$

[CB/Gorbahn/Hermann/Misiak/Stamou/Steinhauser 1311.0903] [2017: f_{B_s} from FLAG, CKM from CKMfitter/UTfit, τ_H^s HFLAV]

Error budget	f_{B_s}	CKM	τ_H^s	m_t	α_s	other param.	non-param.	Σ
2013	4.0%	4.3%	1.3%	1.6%	0.1%	$<$ 0.1%	1.5%	6.4%
2017	3.2%	3.1%	0.6%	1.6%	0.1%	$<$ 0.1%	1.5%	4.7%

Non-parametric uncertainties

- **0.3% from $\mathcal{O}(\alpha_e)$ corrections from $\mu_b \in [m_b/2, 2m_b]$**
- $2 \times 0.2\%$ from $\mathcal{O}(\alpha_s^3, \alpha_e^2, \alpha_s\alpha_e)$ matching corrections from $\mu_0 \in [m_t/2, 2m_t]$
- 0.3% from top-mass conversion from on-shell to $\overline{\rm MS}$ scheme
- 0.5% further uncertainties (power corrections $\mathcal{O}(m_b^2/m_W^2), \ldots$)

!!! used $|V_{cb}|_{\rm incl}$ $\Rightarrow$ rescale $\overline{Br} \propto \left(|V_{cb}|_{\text{your favorite}} \big/ |V_{cb}|_{\rm incl}\right)^2$

- lacking: QED corrections below $\mu_b \Rightarrow$ in principle nonperturbative

QED corrections below $\mu_b \sim m_b$

- b and s quarks: soft residual $\sim \Lambda_{\rm QCD}$
- energetic leptons $E_\ell \sim m_{B_s}/2$ (in B_s-RF)
- hierarchy of modes with virtualities:

$$m_b^2 \quad \to \quad m_b \Lambda_{\rm QCD} \quad \to \quad \Lambda_{\rm QCD}^2 \approx m_\mu^2$$

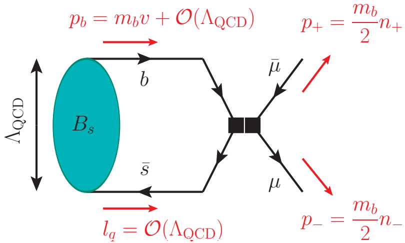
"hard" → "hard-collinear" → "collinear/soft"

full QED → $\text{SCET}_{\rm I}$ → $\text{SCET}_{\rm II}$

$$\lambda \equiv \frac{\Lambda_{\rm QCD}}{m_b} \ll 1$$

⇒ **Soft Collinear EFT = SCET**, but only $\ell = \mu$

Special **external kinematics**



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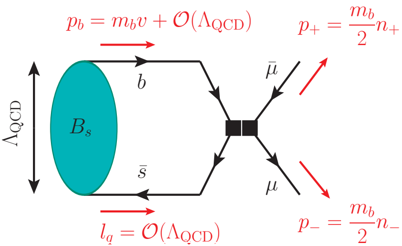
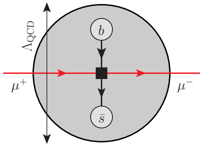


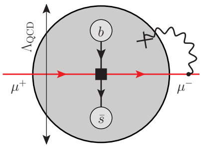
no QED



B_s decay constant

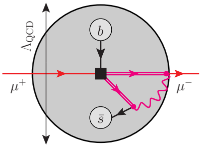
$\langle 0|\bar{s}\gamma_\mu\gamma_5|b|\overline{B}_s\rangle \propto f_{B_s}$

soft photon $\lesssim \Lambda_{\rm QCD}^2$



also $\sim f_{B_s}$
⇒ helicity flip &
local annihilation

hard-collinear photon $\sim m_b\Lambda_{\rm QCD}$

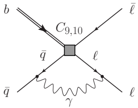


acts as weak probe
⇒ B-meson distribution
amplitude (DA)

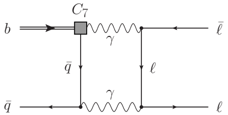
Power-enhanced contribution

Leading QED corrections **in λ-expansion** to $b\bar{s} \to \mu\bar{\mu}$

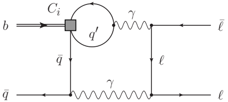
$C_{10} \approx -4$, $C_9 \approx +4$, $C_7 \approx -0.3$



$\mathcal{O}_{9(10)} \propto [\bar{s}\gamma_\mu P_L b][\bar{\ell}\gamma^\mu(\gamma_5)\ell]$



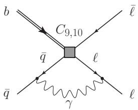
$\mathcal{O}_7 \propto m_b[\bar{s}\sigma_{\mu\nu}P_R b]F^{\mu\nu}$



$\mathcal{O}_i \propto [\bar{s}\Gamma_i P_L b]\sum_q[\bar{q}'\Gamma_i q']$

Power-enhanced contribution

Leading QED corrections **in $\boldsymbol{\lambda}$-expansion** to $b\bar{s} \to \mu\bar{\mu}$ $\quad C_{10} \approx -4,\ C_9 \approx +4,\ C_7 \approx -0.3$



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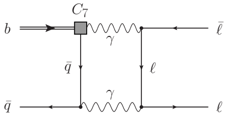

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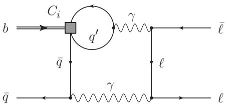

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$$\frac{i\mathcal{A}}{\mathcal{N}} = \overbrace{m_\ell f_{B_q} C_{10}\left[\bar{\ell}\gamma_5\ell\right]}^{\text{LO}} + \frac{\alpha_{\text{em}}}{4\pi} Q_\ell Q_q\, m_\ell f_{B_q} \overbrace{\frac{m_B}{\lambda_B}}^{\text{power-enh.}} \left[\bar{\ell}(1+\gamma_5)\ell\right] \times \Bigg\{$$

$$\int_0^1 du\, \bar{u}\, C_9^{\text{eff}}(um_b^2)\left[L + \ln\frac{u}{\bar{u}} - \sigma_1\right] - Q_\ell C_7^{\text{eff}}\left[\underbrace{L^2}_{\text{large (Log)}^2} - 2L(\sigma_1+1) + 2\sigma_1 + \sigma_2 + \frac{2\pi^2}{3}\right]\Bigg\} + \ldots$$

- power enhancement: $m_B \approx 5$ GeV $\leftrightarrow$ $\lambda_B \approx (0.27 \pm 0.08)$ GeV $\Rightarrow$ $m_B/\lambda_B \approx 18$
- $L \equiv \ln\dfrac{m_b\mu_0}{m_\mu^2}$ with $\mu_0 = 1$ GeV — log (hard-collinear)^2/(collinear)^2 $\Rightarrow L \approx \ln 500 \approx 6$
- only limited knowledge of B-meson DA: $\sigma_1 \approx (1.5 \pm 1.0)$, $\sigma_2 \approx (3 \pm 2)$

$$\frac{1}{\lambda_B(\mu)} = \int_0^\infty \frac{d\omega}{\omega}\phi_{B+}(\omega,\mu) \qquad \frac{\sigma_n(\mu)}{\lambda_B(\mu)} = \int_0^\infty \frac{d\omega}{\omega}\ln^n\frac{\mu_0}{\omega}\phi_{B+}(\omega,\mu)$$

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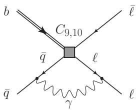
Leading QED corrections **in λ-expansion** to $b\bar{s} \to \mu\bar{\mu}$ $C_{10} \approx -4,\ C_9 \approx +4,\ C_7 \approx -0.3$



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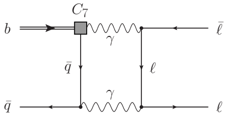

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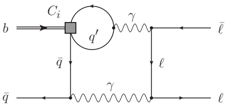

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- Despite cancellation between C_9- and C_7-terms, STILL $(0.3 - 1.1)\%$ reduction of

new SM prediction $\overline{Br}(B_s \to \mu\bar{\mu})_{\text{SM}} = (3.57 \pm 0.17) \times 10^{-9}$

- QED small in: $(\mathcal{A}_{\Delta\Gamma} - 1) \approx 10^{-5}$ and $\mathcal{S} = -0.1\%$ $\Rightarrow$ good prospects to unveil potential NP
- NO power-enhanced contributions to $B_u \to \ell\bar{\nu}_\ell$
- **next steps:** calculate non-power enhanced contributions, deal with $\ell = \tau$ or e, other decays

Controlling hadronic corrections to exclusive $b \to s\ell\bar{\ell}$

CB, Marcin Chrzaszcz, Danny van Dyk and Javier Virto

arXiv:1707.07305

Theory of $B \to K^* \ell\bar{\ell}$

Dipole & Semileptonic op's

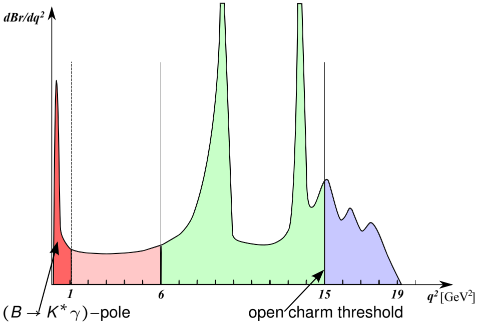
$$\mathcal{O}_{7\gamma(7\gamma')} = m_b[\bar{s}\,\sigma^{\mu\nu} P_{R(L)}\, b] F_{\mu\nu}$$

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

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

Factorisation into form factors (@ LO QED)

$\Rightarrow$ No conceptual problems !!!



@ low q^2: FF's from LCSR — $B \to K$, $B \to K^*$

(10 – 15)% accuracy

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

@ high q^2: FF's from lattice — $B \to K$, $B \to K^*$

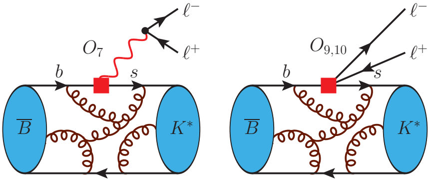
(6 – 9)% accuracy

[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 $B \to K^* \bar{\ell}\ell$



Theory of $B \to K^* \ell\bar{\ell}$

Nonleptonic

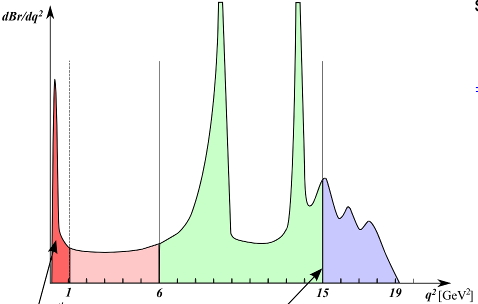
$$\mathcal{O}_{(1)2} = [\bar{s}\,\gamma^{\mu} P_L (T^a)\, c][\bar{c}\,\gamma_{\mu} P_L (T^a)\, b]$$

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

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

at LO in QED

$$\int d^4x\, e^{i\,q\cdot x} \left\langle K^{(*)}_{\lambda} \middle| \mathrm{T}\left\{ j^{\mathrm{em}}_{\mu}(x), \sum_i C_i \mathcal{O}_i(0) \right\} \middle| B(p) \right\rangle$$



$(B \to K^* \gamma)$–pole

open charm threshold

different approaches at

Large Recoil (low-q^2)

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

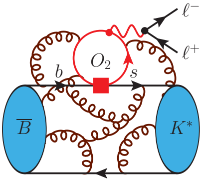
[Beneke/Feldmann/Seidel hep-ph/0106067 + 0412400
Lyon/Zwicky et al. 1212.2242 + 1305.4797
Khodjamirian et al. 1006.4945 + 1211.0234 + 1506.07760]

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



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

Parameterisation of power corrections $\lambda = \pm, 0$

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

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

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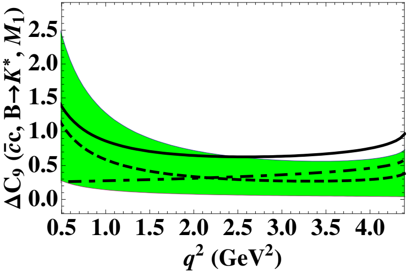
⇒ Soft-gluon emission off $\bar{c}c$-pairs enhanced by tree-level current-current $C_{1,2}$

[Khodjamirian et al. 1006.4945 + 1211.0234 + 1506.07760]



1) contributions to $h_\lambda(q^2)$ via OPE

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

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

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

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

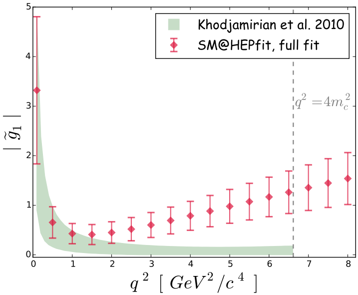
Parameterisation of power corrections $\lambda = \pm, 0$

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

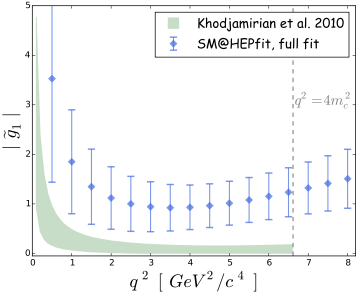
$$\approx \underbrace{[\text{LO in } 1/m_b]}_{\text{QCDF}} + h_\lambda^{(0)} + \frac{q^2}{1\text{GeV}^2} h_\lambda^{(1)} + \frac{q^4}{1\text{GeV}^4} h_\lambda^{(2)}, \qquad h_\lambda^{(0,1,2)} \in \mathbb{C}$$

$\Rightarrow$ Can fit $h_\lambda^{(0,1,2)}$ from data (assuming $C_9^{\text{NP}} = 0$) [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 $q^2 \lesssim 6\ \text{GeV}^2$

Parameterisation of power corrections $\lambda = \pm, 0$

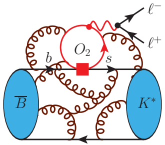
$$h_\lambda(q^2) = \frac{\epsilon^*_\mu(\lambda)}{m_B^2} \int d^4x\, e^{i q\cdot x} \left\langle K_\lambda^{(*)} \middle| T\left\{ j_\mu^{\text{em}}(x), \sum_i C_i \mathcal{O}_i(0) \right\} \middle| B(p) \right\rangle$$

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

- **In global fits:** magnitude of power corrections taken from Khodjamirian/Mannel/Pivovarov/Wang 1006.4945 BUT allowing for both signs
- sign of power corrections predicted by KMPW 2010 increases NP contribution to C_9
- large power corrections can not explain $R_{K,K^*}^{\mu/e}$ measurement

Gaining control over hadronic contribution

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



Decomposition into 3 functions $\mathcal{H}_{\perp,\parallel,0}(q^2)$

$$\mathcal{H}^\mu(p,q) \equiv m_B^2\, \eta_\alpha^* \left[S_\perp^{\alpha\mu} \mathcal{H}_\perp - S_\parallel^{\alpha\mu} \mathcal{H}_\parallel - S_0^{\alpha\mu} \mathcal{H}_0 \right]$$

1) accessible for theory @ $q^2 < 0$

- QCD factorization [Beneke/Feldmann/Seidel hep-ph/0106067 + 0412400]
- soft gluons (LCSRs with B-meson DAs) [Khodjamirian/Mannel/(Pivovarov)/Wang 1006.4945, 1211.0234]

2) contributes to $B \to K^* + (J/\psi, \psi')$

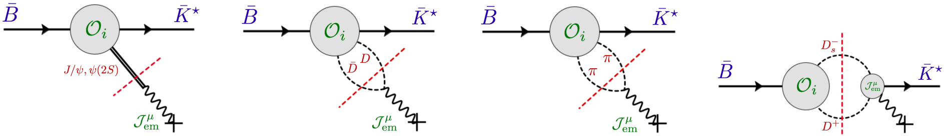
- transversity amplitudes $\mathcal{A}_\lambda{}^{\psi_n}$ measured in angular analysis of $B \to K^* + (J/\psi, \psi')$ by LHCb, BaBar, Belle, CDF
- $\mathcal{H}_\lambda(q^2 \to m_{\psi_n}^2) \sim \dfrac{m_{\psi_n} f_{\psi_n}^* \mathcal{A}_\lambda{}^{\psi_n}}{m_B^2 (q^2 - m_{\psi_n}^2)} + \ldots$

3) contributes to $B \to K^* \mu\bar{\mu}$

- most information expected around J/ψ, ψ' poles,
  where short-distance contributions are comparable or smaller

Parametrization from analyticity

Analytic structure of $\mathcal{H}_\lambda$ given by **poles and branch cuts** from [CB/Chrzaszcz/van Dyk/Virto 1707.07305]



narrow charmonia, assumed to be stable

$D\bar{D}$ production: $q^2 \gtrsim 2m_D$

$\psi \to 3\pi, \ldots$: $q^2 \gtrsim 3m_\pi$ suppressed by OZI

q^2-dep. imaginary due to branch cut in p^2

Use parametrization that respects analytic structure:

- conformal mapping $q^2 \to z(q^2)$ [Boyd/Grinstein/Lebed hep-ph/9412321]
- $\mathcal{H}_\lambda(q^2)/\mathcal{F}(q^2)$ analytic in unit circle $|z| < 1$
  $\Rightarrow$ Taylor expand around $z = 0$, since $|z| < 0.52$ for $-7\,\text{GeV}^2 \leq q^2 \leq 14\,\text{GeV}^2$
- factor out J/ψ, ψ' poles:

$$\mathcal{H}_\lambda(z) = \frac{1 - zz^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - zz^*_{\psi'}}{z - z_{\psi'}} \hat{\mathcal{H}}_\lambda(z)$$

- parametrize actually ratios ($\mathcal{F}_\lambda = B \to K^*$ form factors)

$$\frac{\hat{\mathcal{H}}_\lambda(z)}{\mathcal{F}_\lambda(z)} = \sum_{k=0}^{N} \alpha_k^{(\lambda)} z^k, \qquad \alpha_k^{(\lambda)} \in \text{complex-valued}$$

$\Rightarrow$ take $N = 2 \to 16$ real parameters:
$2 \times (\lambda = 3) \times (k = 0, 1, 2) - 2 = 16$ where $\alpha_0^{(0)} = 0$ since $\mathcal{A}_0[B \to K^* \ell\bar{\ell}](q^2 = 0) = 0$

Determination of $\mathcal{H}_\lambda$

"Prior": Use only **1)** theory at $q^2 < 0$

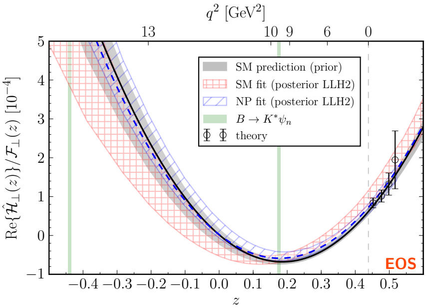
2) data of angular analysis $B \to K^* + (J/\psi, \psi')$

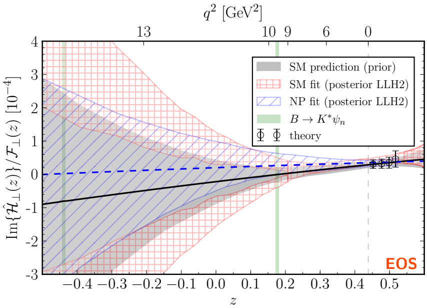
"Posterior": **3)** include spectral data from $B \to K^* \mu\bar{\mu}$ (decay rate & angular observbles)

$\Rightarrow$ assume something about NP

SM fit assume $C_9 = C_9^{\rm SM}$

NP fit assume $C_9 = C_9^{\rm SM} + C_9^{\rm NP}$ with $C_9^{\rm NP} \neq 0$





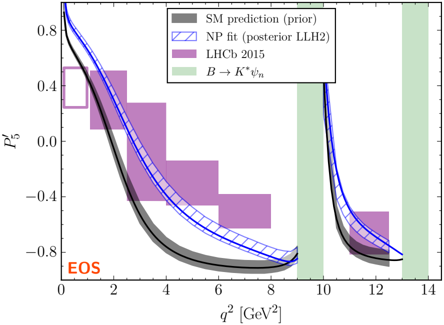
$\Rightarrow$ imaginary part of $\mathcal{H}_\lambda$ less well determined

EOS public repo **https://github.com/eos/eos**

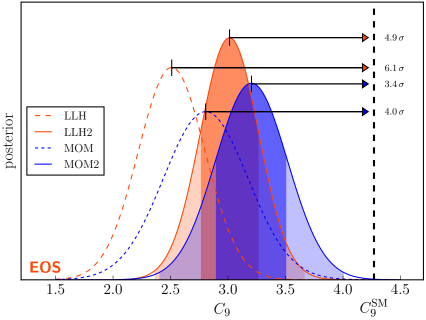
SM predictions + Fit including $B \to K^* \mu\bar{\mu}$ data

LLH = log likelihood & MOM = method of moments measurement

. . . vs. . . . 2 = w/o vs. w/ interresonance bin



Prior- and NP-fit posterior predictions of P_5'



$\Rightarrow$ NP hypotheses with $C_9^{\rm NP} \sim -1$ is favored in global fit

[work in progress]

$\Rightarrow$ Improvable with

- NLO QCD corrections to theory at $q^2 < 0$
- better angular analysis of $B \to K^* \psi_n$
- better spectral information of $B \to K^* \mu\bar{\mu}$ in narrow-resonance region
  $\Rightarrow$ extend the z expansion to $N = 3$ (z^3)
- generalize parametrization to account for small effects from light-hadron cut

Fit for C_9 and $c\bar{c}$ contributions

Sensitivity study [Chrzaszcz/**Mauri**/Serra/Silva Coutinho/van Dyk @ LHCb Implications WS, CERN, Nov. 2017]

- simultaneous fit of C_9^μ and $\mathcal{H}_\lambda(z)$ from $B \to K^*(\mu\bar{\mu})$ data
- $\mathcal{H}_\lambda(z)$ parametrized up to z^2 with / without priors from:
  1) theory constraints at $q^2 < 0$
  2) $B \to K^*(J/\psi, \psi')$ angular distribution
- q^2-unbinned fit of events in $q^2 \in [1.1, 9.0]$ & $[10.0, 13.0]$ GeV^2
- toy generation with 4K events, with z^2 terms only

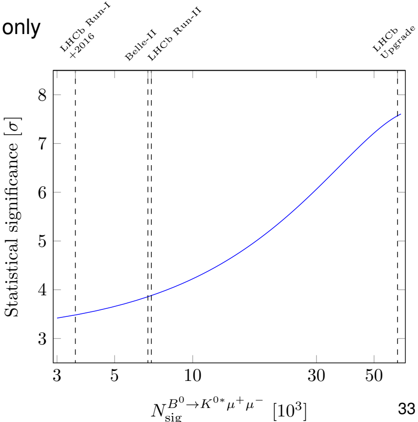
Performing C_9 & $\mathcal{H}_\lambda$ fit only with $B \to K^*\mu\bar{\mu}$

- toys for benchmark point: $C_9^{\rm NP} = -1$
- fit is stable for both: z^2 and z^3
- BUT

$$C_9|_{z^3} - C_9|_{z^2} = 0.17$$

$$\sigma(C_9)|_{z^3} = 0.69 \quad \text{vs.} \quad \sigma(C_9)|_{z^2} = 0.17$$

$\Rightarrow$ need to include priors on $\mathcal{H}_\lambda$

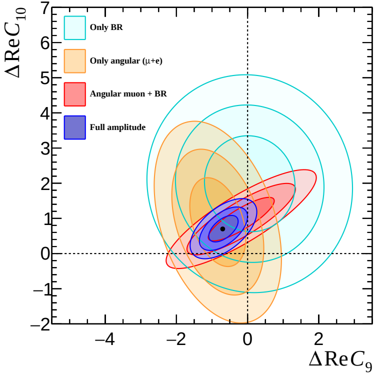


Extension to LFU tests

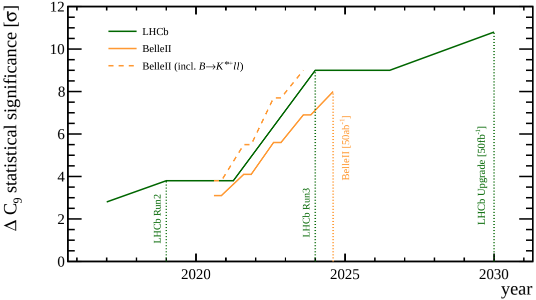
Sensitivity study [**Mauri**/Serra/Silva Coutinho @ $b \to s\ell\bar{\ell}$ WS, MIAPP, Munich, Feb. 2018]

- simultaneous fit of $C_{9,10}^{\mu,e}$ and $\mathcal{H}_\lambda(z)$ from $B \to K^*(\mu\bar{\mu}, e\bar{e})$ data
- common nuisance parameters: FFs, CKM, $\mathcal{H}_\lambda(z)$
- (q^2-unbinned fit of events in

$$\ell = \mu: \; q^2 \in [1.1, 8.0] \;\&\; [11.0, 12.5] \text{ GeV}^2 \qquad \ell = e: \; q^2 \in [1.1, 7.0] \text{ GeV}^2$$



$\Delta C_i \equiv C_i^\mu - C_i^e$



Summary

- **two high-statistics experiments: LHCb** (ongoing) and **Belle II** (starting 2018)
  $\Rightarrow$ high precision era in b-physics
  ... many tests of SM in quark flavor physics

- b-quark physics is an important window to **test flavor structure of SM** = "CKM-picture" and sensitive to high scales $\Rightarrow$ put constraints on NP effects

- currently intriguing hints of violation of lepton flavor universality in
  $\Rightarrow b \to s\ell\bar{\ell}$ ($\ell = e, \mu$) (LHCb)
  $\Rightarrow b \to c\tau\nu_\tau$ in $R(D, D^*, J/\psi)$ (Babar, Belle, LHCb)

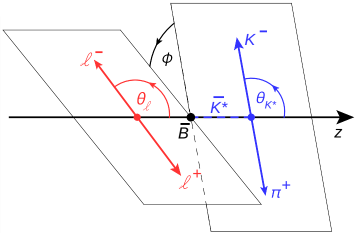
- **QED corrections** to $B_s \to \mu\bar{\mu}$ ($B_u \to \ell\nu_\ell$) for precision predictions with long-distance theory uncertainty $< (1-2)\%$

- gaining control over **non-local matrix elements** to $B \to K^{(*)}\mu\bar{\mu}$ from analyticity:
  simplest parametrization with 2nd order in z expansion supports
  NP contribution in $C_9^{\rm NP} \approx -1$ from $B \to K^*\mu\bar{\mu}$ data alone (w/o $R_{K^{(*)}}^{\mu/e}$)

Backup Slides

Angular observables $J_i(q^2)$ in $B \to K^* [\to K\pi] + \bar{\ell}\ell$

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



Angular observables $J_i(q^2)$ in $B \to K^* [\to K\pi] + \bar{\ell}\ell$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} \simeq J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K$$
$$+(J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell + J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
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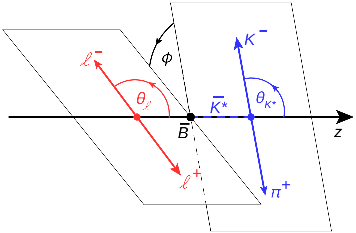

"Optimized observables" $\Rightarrow$ reduced FF sensitivity

- guided by large energy limit @ low-q^2 and Isgur-Wise @ high-q^2 FF-relations
- FF's cancel up to corrections $\sim \Lambda_{\mathrm{QCD}}/m_b$

@ 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]

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

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

Angular observables $J_i(q^2)$ in $B \to K^* [\to K\pi] + \bar{\ell}\ell$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} \simeq J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K$$
$$+(J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell + J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
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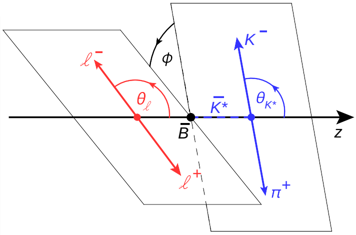
$$+J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi$$



"Optimized observables" $\Rightarrow$ 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 $\sim \Lambda_{\rm QCD}/m_b$

@ high q^2

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

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

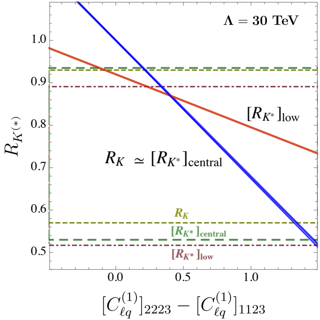
$$H_T^{(2)} \equiv P_5 \equiv \frac{J_5/\sqrt{2}}{\sqrt{-J_{2c}(2J_{2s} + J_3)}} \qquad H_T^{(3)} \equiv \frac{J_{6s}/2}{\sqrt{(2J_{2s})^2 - (J_3)^2}}$$

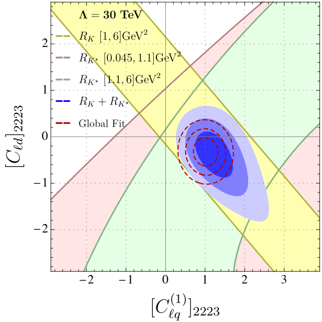
$$H_T^{(4)} \equiv Q \equiv \frac{\sqrt{2}J_8}{\sqrt{-J_{2c}(2J_{2s} + J_3)}} \qquad H_T^{(5)} \equiv \frac{-J_9}{\sqrt{(2J_{2s})^2 - (J_3)^2}}$$

B-anomalies interpreted in SMEFT

[Celis/Fuentes-Martin/Vicente/Virto 1704.05672]

- SMEFT = parametrize NP above EW scale in $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ dim-6 operators
- match on $\Delta B = 1$ EFT $SU(3)_c \otimes U(1)_{\rm em}$ dim-6 operators
- consider **"direct"** effects from semi-leptonic SMEFT operators
  and **"indirect"** effects from top-Yukawa mixing of other SMEFT operators





Dependence of R_{K,K^*} on SMEFT op's $[\bar\mu_L \gamma_\mu \mu_L][\bar s_L \gamma^\mu b_L]$ and $[\bar e_L \gamma_\mu e_L][\bar s_L \gamma^\mu b_L]$

Bounds on Wilson coeff's $\mathcal{C}_{ld}$ vs. $\mathcal{C}_{lq}^{(1)}$, assuming no NP in electron mode

$\Rightarrow$ B-anomalies can be explained with $\mathcal{C}_{lq}^{(1,3)}$ with NP scale as high as $\Lambda_{\rm NP} \sim (30 - 50)$ TeV

$\Rightarrow$ via top-Yukawa-top mixing also $\mathcal{C}_{lu}$ but only for $\Lambda_{\rm NP} \lesssim 1$ TeV

Prospects for LFU in $b \to s\ell\bar{\ell}$

- improvements $R_K[1,6]$ @ **LHCb**: [M. Patel talk @ Instant WS on B anomlies @ CERN 05/2017]
  Run I (3/fb) ~ 250 evts $B^+ \to K^+ e\bar{e}$ → current Run-II (1.9/fb) ~ 800 (twice x-sec, better trigger)
  ⇒ stat. error down by factor 1.8 (current $R_K[1,6] = 0.745^{+0.090}_{-0.074} \pm 0.036$)

- improvements R_{K^*} @ LHCb:
  ⇒ stat. error down by factor 1.5, perhaps high-q^2 bin

- measurement of $R(\phi)$, search for $B \to K^{(*)} + (e\mu,\ \mu\tau, \tau\tau)$ (Run II LHCb = 5 × Run I statistics)

- **Belle II**: independent measurement
  ⇒ $R_{X_s}[1,6]$ uncertainty 12%(4.0%) for 5/ab (50/ab) and similar R_{K,K^*} (statistically dominated)

[Altmannshofer/Stangl/Straub 1704.05435]

- theory proposes **additional observables**

  $D_{P_i'} = P_i'[B \to K^* \mu\bar{\mu}] - P_i'[B \to K^* e\bar{e}]$

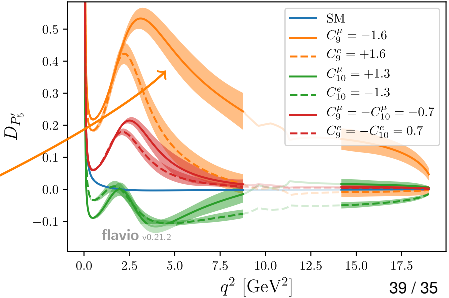
  [Altmannshofer/Yavin 1508.07009, Capdevila et al. 1605.03156]

  P_i' angular observables in $B \to K^* \ell\bar{\ell}$

  ⇒ 1st measurement

  $D_{P_5'}[1,6] = +0.66 \pm 0.50$ [Belle 1612.05014]

  ⇒ very sensitive to C_9^μ



Prospects for $R^{\tau/\ell}_{D^{(*)}}$

Can expect (improved) measurement of

- other ratios $R(X_c,\, D_s,\, \Lambda_c,\, J/\psi)$

  $R(D_s)_{\text{SM}} = 0.301(6)$
  [HPQCD 1703.09728]

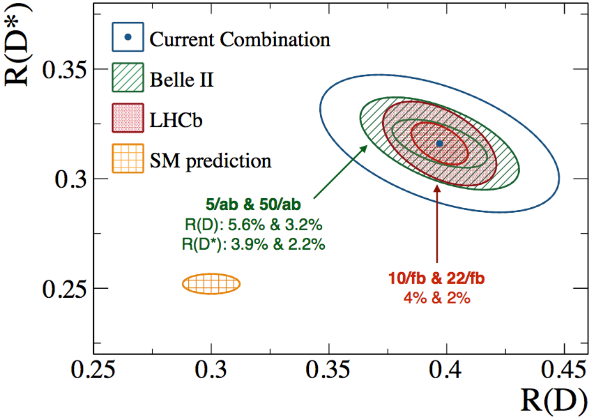
- also $b \to u\tau\nu_\tau$: $R(\pi), \ldots$

  $R(\pi)_{\text{SM}} = 0.641(17)$
  [MILC/FNAL 1510.02349]

- separately test τ/e and τ/μ

- differential q^2-spectrum

[F. Bernlochner talk at SM@LHCb 2017]

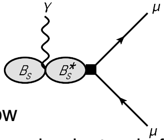


- angular analysis of $B \to [D^{(*)} \to D(\pi,\gamma)]\nu_\tau[\tau \to (\ell\nu,\pi,\rho)\nu_\tau]$
  - D^* polarization
  - τ polarizations
  - τ forward-backward asymmetry

Real QED corrections below $\mu_b \sim m_b$ for $B_q \to \ell\bar{\ell}$

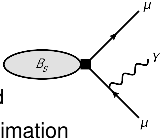
. . . are accounted for in experimental analysis

Initial state radiation



- tiny in signal window
- phase-space suppression instead of helicity suppression
- can be avoided with cuts

Final state radiation



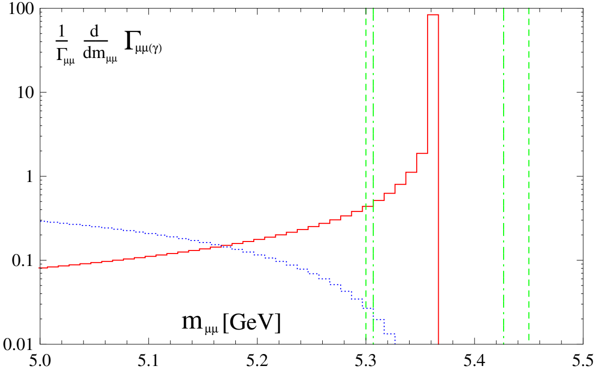
- helicity suppressed
- soft-photon approximation
- extrapolated from signal window over all $m^2_{\mu\bar{\mu}}$ via PHOTOS by LHCb and CMS

ISR [Aditya/Healey/Petrov arXiv:1212.4166]

FSR [Buras et al. arXiv:1208.0934]

experimental signal windows (LHCb, CMS)

[LHCb arXiv:1307.5024, CMS arXiv:1307.5025]



Theory at space-like q^2

Using LCSR setup with (LC = light cone) [Khodjamirian/Mannel/Pivovarov/Wang 1006.4945]

A) B-meson LCDA

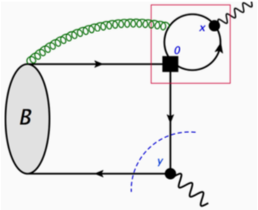
B) light-cone dominance ($x^2 \lesssim 1/(2m_c - \sqrt{q^2})^2$)

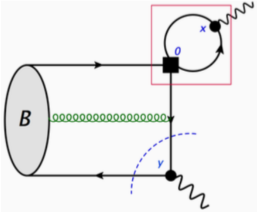
- LC expansion of charm propagator yields [Balitsky/Braun 1989]

$$\sim \left(\frac{C_1}{3} + C_2\right) g(q^2, m_c^2)\,[\bar{s}\,\Gamma\, b] \qquad \leftarrow \text{recover pert. 1-loop}$$

$$+ \text{coeff} \times \underbrace{\left[\bar{s}\gamma_\mu (i n_+ \cdot \mathcal{D})^n \widetilde{G}_{\alpha\beta} P_L\, b\right]}_{\downarrow} + \ldots$$

calculate matrix element with LCSR





- include 3-particle contributions to form factors $\mathcal{F}_\lambda$

Theory at space-like q^2

Using LCSR setup with (LC = light cone) [Khodjamirian/Mannel/Pivovarov/Wang 1006.4945]

A) B-meson LCDA

B) light-cone dominance ($x^2 \lesssim 1/(2m_c - \sqrt{q^2})^2$)

following contributions are known (at LO in QCD)

- $B \to K^*$ form factors [Khodjamirian/Mannel/Pivovarov/Wang 1006.4945]
- soft-gluon corrections to $B \to K^* \gamma$ and $B \to K^{(*)} \ell\bar{\ell}$ from $O_{1,2}^{(c)}$ [Khodjamirian/Mannel/Pivovarov/Wang 1006.4945]
- soft gluon correction to O_8 contribution for $B \to K$ [Khodjamirian/Mannel/Wang 1211.0234]
- results for $\mathcal{H}^{(c)}$ for $B \to K\ell\bar{\ell}$ [Khodjamirian/Mannel/Wang 1211.0234]; $B \to \pi\ell\bar{\ell}$ [Hambrock/Khodjamirian/Rusov 1506.07760]
- results for $\mathcal{H}^{(u)}$ for $B \to \pi\ell\bar{\ell}$ [Hambrock/Khodjamirian/Rusov 1506.07760]

Potential for improvement

- going to NLO in QCD
- including higher twist and higher-particle DA's

Renormalization scale dependence

??? Are there issues for cancellation of μ_b scale dependence between $C_9(\mu_b)$ and $C_{1,2}(\mu_b)$

⇒ No, but the fitted values of parameters depend on the used value for μ_b,
similar to determinations of PDFs (parton distribution functions) in collider physics

Here

- split amplitude in contribution from semi- and non-leptonic operators

$$A = A_{\mathrm{SD}}(C_9; \mu_b) + A_{\mathrm{nonlocal}}(C_{1,2}; \mu_b)$$

- use theory for $A_{\mathrm{SD}}(\mu_b)(C_9; \mu_b)$ with some fixed value for μ_b
- in general — with $M_{1,2}$ non-perturbative

$$A_{\mathrm{nonlocal}}(C_{1,2}; \mu_b) = C_1(\mu_b) M_1(\mu_b) + C_2(\mu_b) M_2(\mu_b)$$

- $A_{\mathrm{nonlocal}}(C_{1,2}; \mu_b)$ expressed in z parametrization and fitted, assuming no NP in $C_{1,2}(\mu_b)$

  ⇒ could also fit for $M_{1,2}(\mu_b)$ using SM values for $C_{1,2}(\mu_b)$,
  but we know only analytic structure of A_{nonlocal}

  → would be more in spirit of collider physics: "hard kernel(μ_f) ⊗ PDF(μ_f)" ($M_{1,2}$ ~PDF)

  → ADM's of $C_{1,2}(\mu_b)$ would determine running of $M_{1,2}(\mu)$

⇒ $A_{\mathrm{nonlocal}}(C_{1,2}; \mu_b)$ is fitted for the chosen particular value of μ_b, which must be used for consistency everywhere throughout the analysis

Prior fit to z parametrization for $N = 2$

[CB/Chrzaszcz/van Dyk/Virto 1707.07305]

k	0	1	2
$\mathrm{Re}[\alpha_k^{(\perp)}]$	-0.06 ± 0.21	-6.77 ± 0.27	18.96 ± 0.59
$\mathrm{Re}[\alpha_k^{(\parallel)}]$	-0.35 ± 0.62	-3.13 ± 0.41	12.20 ± 1.34
$\mathrm{Re}[\alpha_k^{(0)}]$	0.05 ± 1.52	17.26 ± 1.64	–
$\mathrm{Im}[\alpha_k^{(\perp)}]$	-0.21 ± 2.25	1.17 ± 3.58	-0.08 ± 2.24
$\mathrm{Im}[\alpha_k^{(\parallel)}]$	-0.04 ± 3.67	-2.14 ± 2.46	6.03 ± 2.50
$\mathrm{Im}[\alpha_k^{(0)}]$	-0.05 ± 4.99	4.29 ± 3.14	–

Mean values and standard deviations (in units of 10^{-4}) of the prior PDF for the parameters $\alpha_k^{(\lambda)}$

Obtained including

- theory constraints at $q^2 < 0$
- angular analysis of $B \to K^* J/\psi(\to \mu\bar{\mu})$ and $B \to K^* \psi'(\to \mu\bar{\mu})$

$\Rightarrow$ Going to z^3 requires to include $B \to K^* \mu\bar{\mu}$ data for convergence of the fit (posterior fit)

Convergence of z-expansion

Current fit of $\hat{\mathcal{H}}(z)$ for $N = 2$

- remember: $\hat{\mathcal{H}}(z)$ has no poles $\quad \mathcal{H}_\lambda(z) = \frac{1 - z z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z^*_{\psi'}}{z - z_{\psi'}} \hat{\mathcal{H}}_\lambda(z)$

  !!! also in form factor z-parametrisation pole is factored out

- a priori difficult to say whether

  $\hat{\mathcal{H}}(z) \sim \text{const}$
  or $\hat{\mathcal{H}}(z) \sim z$
  or $\hat{\mathcal{H}}(z) \sim z^2$
  or $\hat{\mathcal{H}}(z) \sim z^n$ $(n \geq 3)$

  But would expect higher powers z^n less relevant in considered range
  $|z| < 0.52 \quad \text{for} \quad -7\,\text{GeV}^2 \leq q^2 \leq 14\,\text{GeV}^2$

- current fit shows rather strong $\hat{\mathcal{H}}(z) \sim z^2$, which might be still acceptable

  !!! for form factors find usually closer to linear $\sim z$,
  BUT quadratic terms $\sim z^2$ also needed to fit to lattice and/or LCSR results

  $\Rightarrow$ $\hat{\mathcal{H}}(z)$ is a much more complicated hadronic object than a form factor,
  so why not z^3?

- including $B \to K^* \ell\bar{\ell}$ data the z^n, $n \geq 3$ can be tested, hopefully less relevant

Light-hadron cut

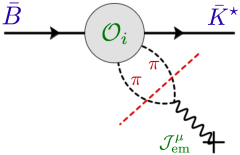
- a brunch cut due to "$c\bar{c} \to gluons \to q\bar{q}$"

  $\Rightarrow$ starts at $\sqrt{q^2} \sim 3m_\pi$

  !!! in QCD only $(N_c - N_{\bar{c}})$ conserved, but not $(N_c + N_{\bar{c}})$

- same mechanism gives rise to very narrow width of J/ψ and ψ'

- assume OZI suppression effective, similar to other decays, however no first-principle methods to prove this



$\Rightarrow$ Current precision of data too limitied to be sensitive to this effect