Prospects with $b \to (d, s)\ell\bar{\ell}$
– theory –

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3rd LHCb Upgrade II Workshop

LAPP – Annecy
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What can we do with 300 fb^{-1} at 14 TeV?

- about 200 × Run I data
- only few sensitivity studies for LHCb for rare $b \to q + (\gamma, \ell\bar{\ell})$ decays available

  $\Rightarrow$ **no definite answers can be given here**

STILL

- many phenomenological studies were proposed in the past,
  — some might "science fiction" at their time —
  could become real science with this amount of data

BECAUSE

- we have access to new observables

  $\Rightarrow$ new tests of SM (= Standard Model)

  $\Rightarrow$ constraints on NP (= New Physics) scenarios

- feasibility of data-driven approaches to hadronic parameters,
  not accessible with first-principle nonperturbative methods

$\Rightarrow$ get very precise and dig for tiny things (really rare decays or tiny observables)

Outline

- Review of $|\Delta B| = 1$ EFT
- Leptonic decays $B_{d,s} \to \ell\bar{\ell}$
- Exclusive $B \to (P, V)\ell\bar{\ell}$

Review of $|\Delta B| = 1$ EFT

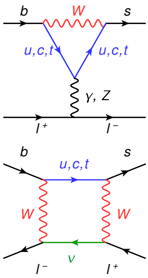
EFT for $b \to q + (\gamma, \ell\bar{\ell})$ in SM

$q = d, s$

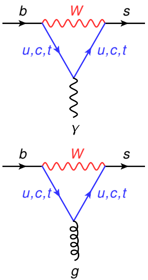
$$\mathcal{L}_{\Delta B=1} \sim V_{tb} V_{tq}^* \Big[\sum_{9,10} C_i^{\ell\bar{\ell}} \mathcal{O}_i^{\ell\bar{\ell}} + \sum_{7\gamma,8g} C_i \mathcal{O}_i + \mathrm{CC} + (\text{QCD \& QED-peng}) \Big]$$
$$+ V_{ub} V_{uq}^* \big[\mathrm{CC}^u - \mathrm{CC}^c \big]$$

In the SM various operators

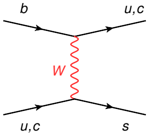
semi-leptonic



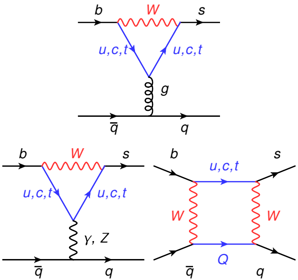
QCD & QED -dipole



charged current



QCD & QED -penguin



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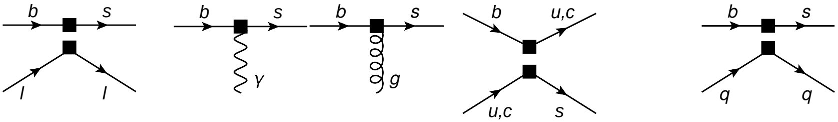
$$+ V_{ub} V_{uq}^* \big[\text{CC}^u - \text{CC}^c \big]$$

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

$\mathcal{O}_i =$ higher-dim. operators: flavour-changing coupling of light quarks

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

$q = d, s$

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

CP asymmetries in SM given by CKM hierarchies

Cabibbo angle $\lambda_C \approx 0.2$

$q = s$

$$V_{tb} V_{ts}^* \approx -V_{cb} V_{cs}^* \sim \lambda_C^2 A$$

$$V_{ub} V_{us}^* \sim \lambda_C^4 A(\rho - i\eta)$$

$A_{\text{CP}} \lesssim 1\%$

[CB/Hiller/Piranishvili 0805.2525]

$\Rightarrow$ CPA's in $b \to s\ell\bar{\ell}$ suppressed in SM with λ_C^2

$q = d$

$$V_{tb} V_{td}^* \sim \lambda_C^3 A(1 - \rho - i\eta)$$

$$V_{cb} V_{cd}^* \sim \lambda_C$$

$$V_{ub} V_{ud}^* \sim \lambda_C^3 A(\rho - i\eta)$$

$A_{\text{CP}} \lesssim 20\%$

[Hambrock/Khodjamirian/Rusov 1506.07760]

$\Rightarrow$ CPA's in $b \to d\ell\bar{\ell}$ in SM largish

$\Rightarrow$ Continue to measure CP asymmetries and improve bounds

EFT beyond the SM

$\Rightarrow$ allow all Lorentz & $\mathrm{SU}(3)_c \otimes \mathrm{U}(1)_{em}$-invariant $|\Delta B| = |\Delta Q| = 1$ operators

$$\mathcal{L}^{\rm NP}_{\Delta B=1} = C_{7\gamma} O_{7\gamma} + \sum_{\substack{i=9,10,S,P,T \\ \ell,\ell'=e,\mu,\tau}} C_i^{\ell\ell'} O_i^{\ell\ell'} + \sum_{k=\rm hadr} C_k O_k + (P_L \leftrightarrow P_R)$$

- $O_{7\gamma}^{(\prime)}$ **electro-magnetic dipole:** $\propto m_{b,q} [\bar{q}\sigma_{\mu\nu} P_{R(L)} b] F^{\mu\nu}$

  $\Rightarrow$ strongest constraint on $C_{7,7'}$ from $Br(B \to X_s \gamma)$

- **semi-leptonic operators:** $\propto [\bar{q}\,\Gamma_{qb}\, b][\bar{\ell}\,\Gamma_{\ell\ell'}\,\ell']$

  - $\Gamma_{qb} \otimes \Gamma_{\ell\ell'} = \gamma_\mu P_{L/R} \otimes \gamma^\mu (\gamma_5)$ left- and right-handed curr. $C_{9(10)}^{\ell\ell'}$ and $C_{9'(10')}^{\ell\ell'}$
  - $\Gamma_{qb} \otimes \Gamma_{\ell\ell'} = P_{R/L} \otimes 1(\gamma_5)$ (pseudo-) scalar curr. $C_{S(P)}^{\ell\ell'}$ and $C_{S'(P')}^{\ell\ell'}$
  - $\Gamma_{qb} \otimes \Gamma_{\ell\ell'} = \sigma_{\mu\nu} \otimes \sigma^{\mu\nu}(\gamma_5)$ (pseudo-) tensor curr. $C_{T(T5)}^{\ell\ell'}$

- **hadronic operators:** 1) current-current, 2) QCD & QED-penguins, 3) chromo-magnetic dipole

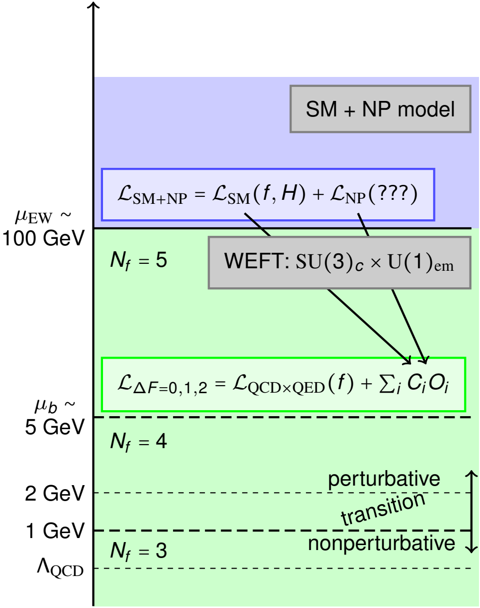
  $\Rightarrow$ usually assumed: **NO** new physics here

$\Rightarrow$ $b \to s\mu\bar{\mu}$ data already sufficient to fully constrain $|C_i^{\mu\mu}|$ for $i = 7, 9, 10, S, P, T, T5$ + χ-flipped

[Beaujean/CB/Jahn 1508.01526]

$\Rightarrow$ Continue for $\ell = \mu$ and try for $\ell = e, \tau$

Factorization via stack of effective theories (EFT)

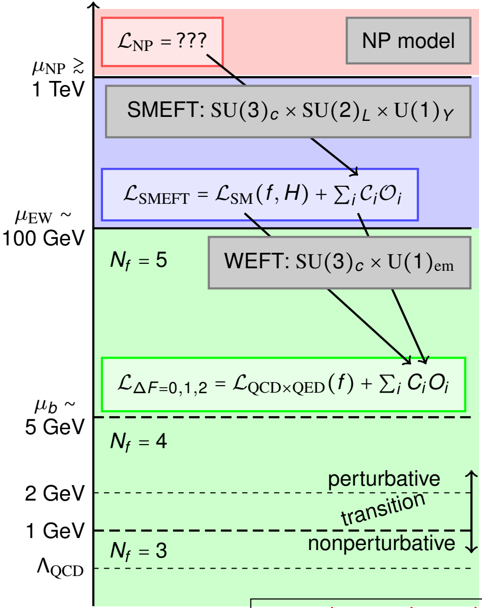


- decoupling of SM and potential NP at electroweak scale μ_{EW}
- assumes no other (relevant) light particles below μ_{EW} (some Z', ...)

WEFT (weak EFT)

- **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 QCD
    - light-cone sum rules (LCSR)
- **number of op's** ($L + B$ conserving)
  dim-5: 70, dim-6: 3631
  [Jenkins/Manohar/Stoffer 1709.04486]

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
- number of op's ($L + B$ conserving)
  dim-5: 1, dim-6: 2499
- 1-loop RGE [Alonso/Jenkins/Manohar/Trott 1312.2014]

WEFT (weak EFT)

- **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
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- **number of op's** ($L + B$ conserving)
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  [Jenkins/Manohar/Stoffer 1709.04486]

⇒ need many observables to constrain all op's

$b \to (d, s) + \ell\bar{\ell}$ processes & observables

process	$b \to s$	$b \to d$
$B \to \gamma\gamma$	$B_s \to \gamma\gamma$	$B \to \gamma\gamma$
$B \to V\gamma$	$B \to K^*(\to K\pi)\gamma$	$B_s \to \phi\gamma$
$B \to \ell\bar{\ell}(\gamma)$	$B_s \to \ell\bar{\ell}(\gamma)$	$B \to \ell\bar{\ell}(\gamma)$
$B \to P\ell\bar{\ell}$	$B \to K\ell\bar{\ell}$	$B \to \pi\ell\bar{\ell}$
	$B_s \to \eta\ell\bar{\ell}$	$B_s \to K\ell\bar{\ell}$
$B \to V(\to P_1P_2)\ell\bar{\ell}$	$B \to K^*(\to K\pi)\ell\bar{\ell}$	$B \to \rho(\to \pi\pi)\ell\bar{\ell}$
	$B_s \to \phi(\to KK)\ell\bar{\ell}$	$B_s \to K^*(\to K\pi)\ell\bar{\ell}$
$B \to X_q\ell\bar{\ell}$	$B \to X_s\ell\bar{\ell}$	$B \to X_d\ell\bar{\ell}$
$\Lambda_b \to \Lambda\ell\bar{\ell}$	$\Lambda_b \to \Lambda\ell\bar{\ell}$	

not exhaustive

- **angular distributions** $\Rightarrow$ maximal information on Wilson coefficients
- **CP-averaged vs. CP-asymmetric** measurements
- **time-dependent measurements**

  $\Rightarrow$ mixing-induced CPA's S

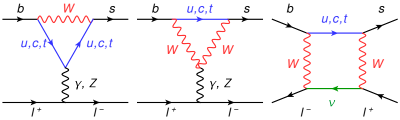
  $\Rightarrow$ for B_s ($\Delta\Gamma_s \neq 0$): mass-eigenstate rate asy's $A_{\Delta\Gamma} \leftrightarrow$ eff. lifetimes [De Bruyn et al. 1204.1735]
  no flavor tagging required

Leptonic decays $B_{d,s} \to \ell\bar{\ell}$

Motivation to study $B_q \to \ell\bar{\ell}$

- **test of SM**

  at loop-level (FCNC) $\propto |V_{tb} V_{tq}^*|^2$



- **helicity suppressed** $\Rightarrow$ sensitive to NP (pseudo-) scalar interactions

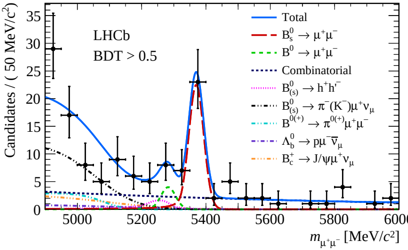
- **observables** Br + time-dependent $A_{\Delta\Gamma}$ (no flavor-tagging) & S for $q = s$, C requires lepton pol.

- **experimental measurement**

$$\overline{Br}(B_s \to \mu\bar{\mu}) = (3.0 \pm 0.5) \times 10^{-9}$$
$$\mathcal{A}_{\Delta\Gamma}(B_s \to \mu\bar{\mu}) = 8.24 \pm 10.72$$

LHCb measured mass-eigenstate rate asymmetry

[CMS 1307.5025, LHCb 1307.5024, 1703.05747]



- **tests of LFV** $\Rightarrow$ SM predicts zero for $B_q \to \ell_i \bar{\ell}_j$ for $i \neq j$

- **experimental prospects** $\Rightarrow$ yesterdays talk by Albert Puig Navarro

Golden theory channel

- **perturbative corrections under control**
  - at μ_W: NLO EW + NNLO QCD [CB/Gorbahn/Stamou 1311.1348, Hermann/Misiak/Steinhauser 1311.1347]
  - $\mu_W \to \mu_b$: RGE NLO QED + NNLO QCD [CB/Gambino/Gorbahn/Haisch hep-ph/0312090]
  - $\mu_b \to \Lambda_{\rm QCD}$: **power-enhanced QED correction** $\delta Br \sim \mathcal{O}(-1\%)$ [Beneke/CB/Szafron 1708.09152]

- **hadronic uncertainty** only decay constant f_{B_q} (at LO in QED)

  $\Rightarrow$ lattice $\delta f_{B_q} \lesssim 0.5\%$: $f_{B_d} = (189.4 \pm 1.4)$ MeV & $f_{B_s} = (230.7 \pm 1.2)$ MeV [FNAL/MILC 1712.09262]

  !!! 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)

- **Error budget** [2017: f_{B_s} from FLAG, CKM from CKMfitter/UTfit, τ_H^s HFLAV]

$$10^9 \times \overline{Br}(B_s \to \mu\bar\mu)_{\rm SM} = 3.57 \pm 0.022|_{\tau_H^s} \pm 0.116|_{f_{B_s}} \pm 0.053|_{\rm non-pmr} \pm 0.030|_{\rm pmr-PE-QED}$$
$$\pm 0.039|_{m_t} \pm 0.111|_{V_{cb}} \pm 0.003|_{\alpha_s}$$

- **Non-parametric (non-pmr) uncertainties** [CB/Gorbahn/Hermann/Misiak/Stamou/Steinhauser 1311.0903]
  - 0.3% non-power-enhanced QED 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 $\mu_W \in [m_t/2,\, 2m_t]$
  - 0.3% from top-mass conversion from on-shell to $\overline{\rm MS}$ scheme
  - 0.5% further uncertainties (power corrections to EW OPE $\mathcal{O}(m_b^2/m_W^2), \ldots$)

- **QED corrections below $\Lambda_{\rm QCD}$** $\Rightarrow$ currently accounted for by PHOTOS in LHCb/CMS/ATLAS

$\Rightarrow$ theoretical control $\delta Br \lesssim 2\%$ possible, access to short-dist. via $Br \sim |V_{tb} V_{tq}^*|^2 \times |C_{10}(m_t^{\rm MS})|^2$

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

- in principle 3 CPA's with $|C^\lambda|^2 + |S^\lambda|^2 + |A^\lambda_{\Delta\Gamma}|^2 = 1$

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

- $A_{\Delta\Gamma}$ 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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[Fleischer/Galarraga Espinosa/Jaarsma/Tetlalmatzi-Xolocotzi 1709.04735]

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

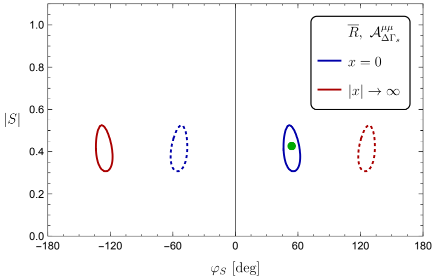
  Benchmark measurement

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

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

  dashed: ruled out by S

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



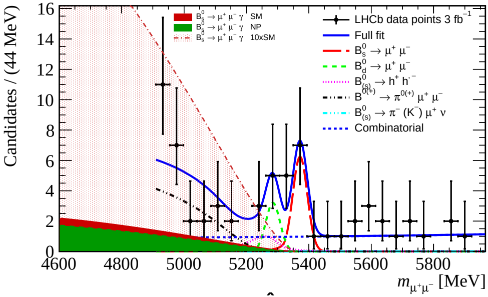
$B_s \to (e\bar{e}, \mu\bar{\mu}) + \gamma$

- $B_s \to \ell\bar{\ell}\gamma$ no helicity suppr. compared to $B_s \to \ell\bar{\ell}$, but α_e suppr.

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

[Dettori/Guadagnoli/Reboud 1610.00629]

extract $Br(B_s \to \mu\bar{\mu}\gamma)$ in fit of $m_{\mu\bar{\mu}}$ spectrum in $B_s \to \mu\bar{\mu}$ including it as additional background component



LFU test in $B_s \to \mu\bar{\mu}\gamma / B_s \to e\bar{e}\gamma$

[Guadagnoli/Reboud/Zwicky]

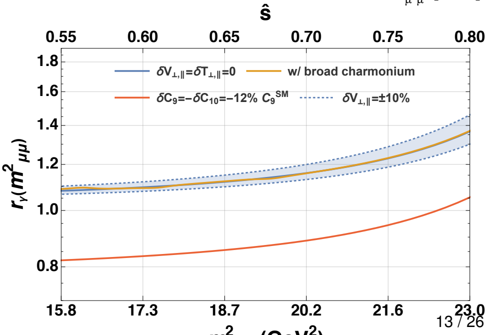
$$R_\gamma^{\mu/e}|_{[\hat{s}_1,\hat{s}_2]} = \frac{Br[B_s \to \mu\bar{\mu}\gamma]_{[\hat{s}_1,\hat{s}_2]}}{Br[B_s \to e\bar{e}\gamma]_{[\hat{s}_1,\hat{s}_2]}}$$

discussion of low- and high-q^2 regions ($q = p_B - p_\gamma$, $\hat{s} = q^2/m_B^2$)

$$R_\gamma^{\mu/e}|_{[0.55,0.8]} = 1.15 \pm 0.03$$

$$Br[B_s \to \mu\bar{\mu}\gamma]_{\text{lo } q^2} = (8.4 \pm 1.3) \times 10^{-9}$$

$$Br[B_s \to \mu\bar{\mu}\gamma]_{\text{hi } q^2} = (8.9 \pm 1.0) \times 10^{-10}$$



Exclusive $B \to (P, V)\ell\bar{\ell}$

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

Dipole & Semileptonic op's

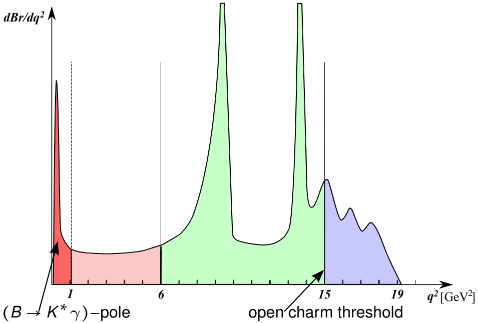
$$\mathcal{O}_{7\gamma(7\gamma')} = m_b[\bar{q}\,\sigma^{\mu\nu} P_{R(L)}\, b] F_{\mu\nu}$$

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

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

Factorisation into form factors (@ LO QED)

⇒ No conceptual problems !!!



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

(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 — $B \to K, \pi$, $B \to K^*$

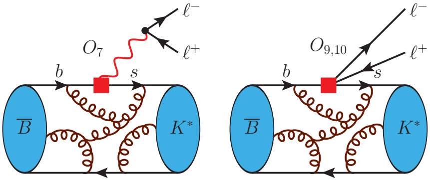
(6 – 9)% accuracy

[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 ⇒ reduce their number
- valid up to $\Lambda_{\rm QCD}/m_b \simeq 0.5/4 \approx 13\%$

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



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

Nonleptonic

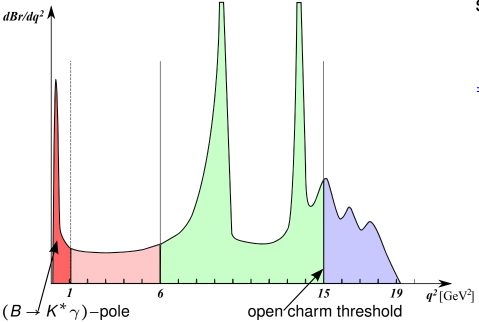
$$\mathcal{O}_{(1)2} = [\bar{q}\,\gamma^\mu P_L (T^a)\, c][\bar{c}\,\gamma_\mu P_L (T^a)\, b]$$

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

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

at LO in QED

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



different approaches at

Large Recoil (low-q^2)

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

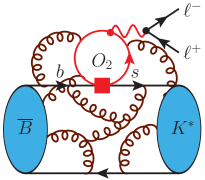
[Beneke/Feldmann/Seidel hep-ph/0106067 + 0412400
Lyon/Zwicky et al. 1212.2242 + 1305.4797
Khodjamirian et al. 1006.4945 + 1211.0234 + 1506.07760]

Low Recoil (high-q^2)

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

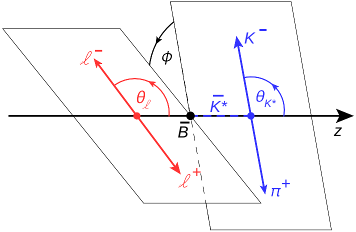
[Grinstein/Pirjol hep-ph/0404250
Beylich/Buchalla/Feldmann 1101.5118]

$\Rightarrow$ least understood theoretical uncertainties



Angular distributions $B \to V\ell\bar{\ell}$

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



- 12 CPav + 12 CPasy **angular ob's** from $J_i(q^2)$ and $\bar{J}_i(q^2)$
  $\Rightarrow$ key to constrain all Wilson coefficients
- current **likelihood fit** of J_i assumes "simple" angular dependence above

BUT

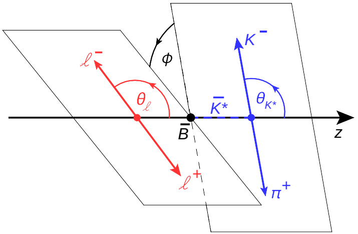
- **only true** at LO QED and when restricting to dim-6 in electroweak OPE

  beyond that more general dependence: $\frac{d^4\Gamma[B \to K^*(\to K\pi)\ell\bar{\ell}]}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = J(q^2, \cos\theta_\ell, \cos\theta_K, \phi)$
- for LHCb upgrade maybe use **method of moments** [Beaujean/Chraszcz/Serra/van Dyk 1503.04100]
- see QED corr's to $d^2\Gamma[B \to X_s\ell\bar{\ell}]/dq^2\, d\cos\theta_\ell$ [Huber/Hurth/Lunghi 1503.04849]

$\Rightarrow$ Need to verify if both methods yield same results

Angular distributions $B \to V\ell\bar{\ell}$

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



"Optimized" observables $\Rightarrow$ 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

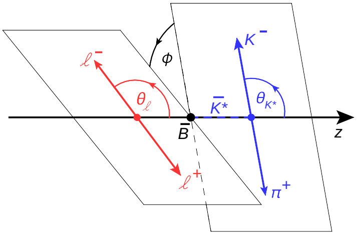
[Krüger/Matias hep-ph/0502060, Egede/Hurth/Matias/Ramon/Reece arXiv:0807.2589 + 1005.0571]
[Becirevic/Schneider arXiv:1106.3283]
[Matias/Mescia/Ramon/Virto arXiv:1202.4266]
[Descotes-Genon/Matias/Ramon/Virto arXiv:1207.2753]

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

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

Angular distributions $B \to V\ell\bar{\ell}$

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



"Optimized" observables $\Rightarrow$ 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]

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

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

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

Relations between angular observables

- given by theory $\Rightarrow$ consistency check of measurement
- can change depending on type of NP effects $\Rightarrow$ distinguish NP operators
- access to hadronic param's (FFs, power corr's, etc.) $\Rightarrow$ data-driven methods

general / low-q^2

[Egede/Hurth/Matias/Ramon/Reece 1005.0571, Matias/Mescia/Ramon/Virto 1202.4266, Matias/Serra 1402.6855]

- $B \to K^* \ell\bar{\ell}$ transversity amplitudes fulfill symmetries
- If $C^{(\prime)}_{S,P,T} = 0$ then out of 12 angular obs's $J_i(q^2)$

  $\Rightarrow$ only 8 (10) of them independent for $m_\ell = 0$ ($m_\ell \neq 0$)

$$J_{1s} = 3J_{2s}, \quad J_{1c} = -J_{2c}, \quad J_{6c} = 0, \quad J_{2c} = \ldots$$

- in general case can choose at low-q^2:

  $\Rightarrow$ 10 optimized and 2 non-optimized observables

$$\{d\Gamma/dq^2, A_{\rm FB}, P_1, \ldots P_6, M_1, M_2, S_1, S_2\}$$

Relations between angular observables

- given by theory $\Rightarrow$ consistency check of measurement
- can change depending on type of NP effects $\Rightarrow$ distinguish NP operators
- access to hadronic param's (FFs, power corr's, etc.) $\Rightarrow$ data-driven methods

high-q^2

- follow from local OPE $\Rightarrow$ approximate, but corrections small [Grinstein/Pirjol hep-ph/0404250]
- check level of violation $\rightarrow$ test for large duality violation [CB/Hiller/van Dyk 1006.5013, 1212.2321]

Scenario	$\lvert H_T^{(1)}\rvert = 1$	$H_T^{(2)} = H_T^{(3)}$	$H_T^{(4)} = H_T^{(5)}$	$J_{6c} = 0$	$J_7 = 0$	$J_{8,9} = 0$
SM	✓	✓	(✓)	✓	✓	✓
SM + (S+P)	✓	$\frac{m_\ell}{Q}\,\Re C_{79}\Delta_S^*$	(✓)	$\frac{m_\ell}{Q}\,\Re C_{79}\Delta_S^*$	$\frac{m_\ell}{Q}\,\Im C_{79}\Delta_S^*$	✓
SM + (T+T5)	$\frac{\Lambda^2}{Q^2}\rho_1^T$	$\frac{m_\ell}{Q}\,\Re C_{10} C_{T(T5)}^*$	(✓)	$\frac{m_\ell}{Q}\,\Re C_{10} C_T^*$	$\frac{m_\ell}{Q}\,\Im C_{10} C_{T5}^*$	✓
SM + SM'	✓	✓	✓	✓	✓	$\Im\rho_2$
all	$\frac{\Lambda^2}{Q^2}\rho_1^T$	$\Re C_{T(T5)}\Delta_{P(S)}^*$	$\frac{\Lambda}{Q}\rho_1^T\,\Im\rho_2$	$\Re C_{T(T5)}\Delta_{P(S)}^*$	$\Im C_{T(T5)}\Delta_{S(P)}^*$	$\Im\rho_2$

✓ ... valid up to corrections $\alpha_s\Lambda/m_b \sim 0.02$ and $C_7/C_9 \times \Lambda/m_b \sim 0.01$

(✓) ... even $H_T^{(4,5)} = 0$ up to above corrections

$\Lambda = \Lambda_{\rm QCD}$, $\quad Q = \mathcal{O}(m_b, \sqrt{q^2})$, $\quad \rho_1^T \propto |C_T|^2 + |C_{T5}|^2$, $\quad \rho_2 \equiv \Re(C_{79} C_{10}^*)$, $\quad \Delta_{S,P} \equiv C_{S,P} - C_{S',P'}$

Relations between angular observables

- given by theory ⇒ consistency check of measurement
- can change depending on type of NP effects ⇒ distinguish NP operators
- access to hadronic param's (FFs, power corr's, etc.) ⇒ data-driven methods

endpoint-relations [Hiller/Zwicky 1312.1923]

- follow from Lorentz-invariance ⇒ strict relations at $q^2_{\rm max}$

$$2J_{2s} = -J_{2c} = -J_3 = J_4, \quad J_{5,6s,6c,7,8,9} = 0, \quad J_{1s} - J_{2s}/3 = J_{1c} - J_{2c}/3, \quad \dots$$

- do not impose them in fits and check after fit whether fulfilled
  ⇒ consistency check of experimental analyses

- close to endpoint expansion in small momentum of V meson
  ⇒ relations between J_i, depending on NP scenario

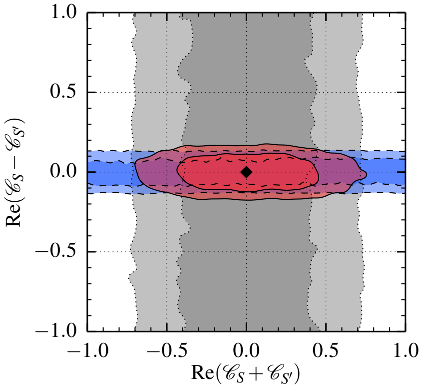
Constraints on scalar & tensorial couplings

In some angular observables **vectorial couplings** suppressed by $m_\ell/\sqrt{q^2}$

- $B_q \to \ell\bar{\ell}$: Br, $A_{\Delta\Gamma}$, S
- $B \to P\ell\bar{\ell}$: F_H, $A_{\rm FB}$
- $B \to V\ell\bar{\ell}$: $(J_{1s} - 3J_{2s})$, $(J_{1c} + J_{2c})$, J_{6c}

$\Rightarrow$ enhanced sensitivity to $C^{(\prime)}_{S,P,T}$

- current data from $B_s \to \mu\bar{\mu}$ and $B \to K\mu\bar{\mu}$ already allow to bound simultaneously all complex-valued $C^{(\prime)}_{S,P,T}$
  [Beaujean/CB/Jahn 1508.01526]
- for $B \to K^*\mu\bar{\mu}$ current likelihood fits assume $C^{(\prime)}_{S,P,T} = 0$
  $\Rightarrow$ should use method of moments for
  $(J_{1s} - 3J_{2s})$, $(J_{1c} + J_{2c})$, J_{6c}



Constraints from

$$Br(B_s \to \mu\bar{\mu}) \propto |C_S - C_{S'}|^2$$

$$F_H(B^+ \to K^+\mu\bar{\mu}) \propto |C_S + C_{S'}|^2$$

Time-dependent analyses

[Descotes-Genon/Virto 1502.05509]

- most interesting modes: $B_d \to K^{*0}(\to K_S \pi^0)\ell\bar{\ell}$, $B_s \to \phi(\to K_S K_L$ or $K^+K^-)\ell\bar{\ell}$
- time-integrated CP-av & CP-asy:

$$J_i + \bar{J}_i \to \frac{J_i + \bar{J}_i}{1-y^2} \qquad J_i - \bar{J}_i \to \frac{J_i + \bar{J}_i}{1+x^2} \qquad \text{with} \qquad y \equiv \frac{\Delta\Gamma_q}{2\Gamma_q} \qquad x \equiv \frac{\Delta M_q}{\Gamma_q}$$

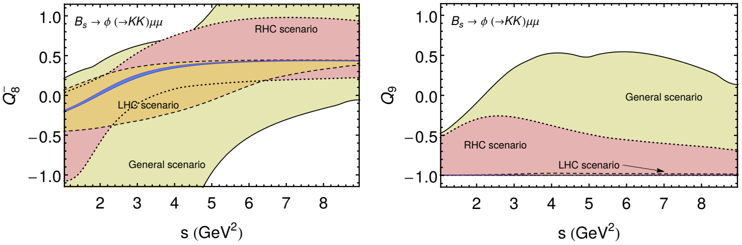
- at LHCb **new angular ob's s_i, h_i**, apart of J_i, $\bar{J}_i$ from flavor-specific decays
  $\Rightarrow$ requires time-dependent measurements
- observables with small SM uncertainties: Q_8^- and Q_9 (RH)

$$Q_8^- \equiv \frac{s_8}{\sqrt{-2(J_{2c}+\tilde{J}_{c2})[2(J_{2s}+\tilde{J}_{2s})-(J_3+\tilde{J}_3)]}} \qquad Q_9 \equiv \frac{s_9}{2(J_{2s}+\tilde{J}_{2s})}$$

SM prediction

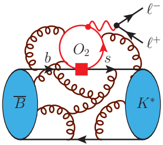
LHC: $C^{\rm NP}_{7,9,10} \neq 0$

RHC: $C^{\rm NP}_{7',9',10'} \neq 0$



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

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

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

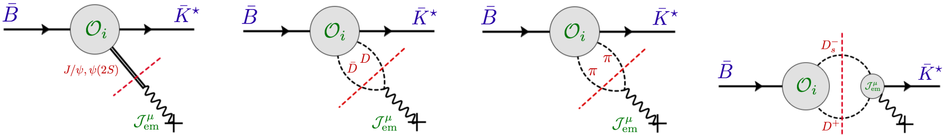
- transversity amplitudes $\mathcal{A}_\lambda{}^{\psi_n}$ measured in angular analysis of $B \to K^* + (J/\psi, \psi')$ by LHCb, BaBar, Belle, CDF
- $\mathcal{H}_\lambda(q^2 \to m_{\psi_n}^2) \sim \dfrac{m_{\psi_n} f_{\psi_n}^* \mathcal{A}_\lambda{}^{\psi_n}}{m_B^2(q^2 - m_{\psi_n}^2)} + \ldots$

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

$D\overline{D}$ 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 $q^2 < 0$

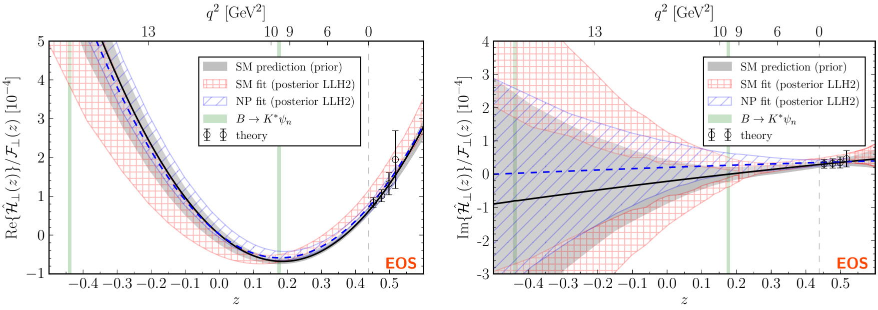
2) data of angular analysis $B \to K^* + (J/\psi, \psi')$

"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**

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

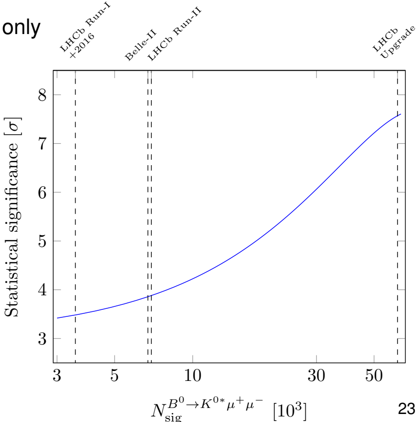
Performing C_9 & $\mathcal{H}_\lambda$ fit only with $B \to K^*\mu\bar{\mu}$

- toys for benchmark point: $C_9^{\text{NP}} = -1$
- 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 $\mathcal{H}_\lambda$



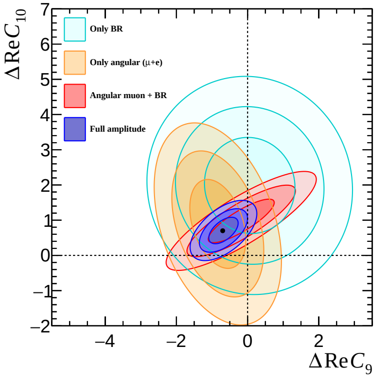
Extension to LFU tests

Sensitivity study

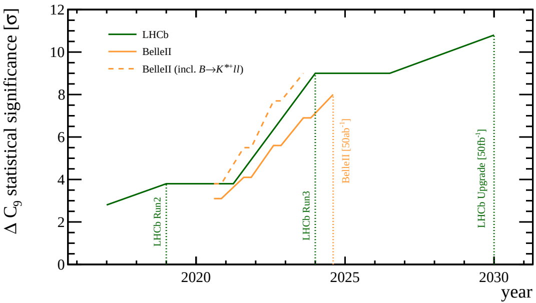
[**Mauri**/Serra/Silva Coutinho @ $b \to s\ell\bar{\ell}$ WS, MIAPP, Munich, Feb. 2018]

- 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

$\ell = \mu$: $q^2 \in [1.1, 8.0]$ & $[11.0, 12.5]$ GeV^2 $\quad$ $\ell = e$: $q^2 \in [1.1, 7.0]$ GeV^2



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



Hadronic contributions to $b \to d\ell\bar{\ell}$

[Hambrock/Khodjamirian/Rusov 1506.07760]

- **up-quark current-current** operators important in $b \to d\ell\bar{\ell}$ because $V_{ub}V_{ud}^* \sim V_{tb}V_{td}^*$
  $\Rightarrow$ at $q^2 \lesssim 1$ GeV^2 contributions $B \to \pi + (u\bar{u})$ to $\mathcal{H}^{(u)}$ with $u\bar{u} = (\rho, \omega, \phi)$
- currently $B \to \pi + (u\bar{u})$ "modelled" with QCDF results from [Beneke/Neubert hep-ph/0308039]
  $\Rightarrow$ could use also measurements (LHCb, Belle II)
- use dispersion relation to calculate $\mathcal{H}^{(u,c)}$ in physical region $4m_\ell^2 \geq q^2$ from calculation at $q^2 < 0$

Alternatively

- can use also **parametrization based on analyticity** for $\mathcal{H}^{(u,c)}$
  $\Rightarrow$ need measurements of $B \to \pi + (\rho, \omega, \phi; J/\psi, \psi')$

  $\to$ still some home works to do

Summary

- $b \to q\ell\bar{\ell}'$ processes constrain Wilson coefficients
  $\to$ SM predicts zero for most of them
  $\Rightarrow$ measure as many as possible observables / processes

- there are some solid theory predictions
  $\Rightarrow$ $B_q \to \ell\bar{\ell}$ (theory golden channel, $\delta Br \lesssim 2\%$, $A_{\Delta\Gamma}$)
  $\Rightarrow$ LFU ratios $R^{\mu/e}_{K,K*}$ + optimized versions
  [Altmannshofer/Yavin 1508.07009, Capdevila/Descotes-Genon/Matias/Virto 1605.03156]

- relations between angular observables in $B \to V(\to P_1 P_2)\ell\bar{\ell}$ to be tested
  $\Rightarrow$ discriminating NP scenarios
  $\Rightarrow$ testing hadronic contributions and local OPE at high q^2

- data-driven approach to hadronic contributions to $B \to (P, V)\ell\bar{\ell}$:
  $\Rightarrow$ parametrization allows to fit them simultaneously with NP from data
  $\Rightarrow$ requires also measurement of angular analyses of $B \to (P, V) + (c\bar{c}, u\bar{u})$

See also presentations at previous workshops

Backup Slides

Tensions and NP interpretation

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]

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

$$R_H^{\mu/e} \equiv \frac{Br[B \to H\mu\bar{\mu}]_{[q_a^2, q_b^2]}}{Br[B \to He\bar{e}]_{[q_a^2, q_b^2]}} \qquad H = K, K^*, \phi, X_s, \ldots$$

[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]

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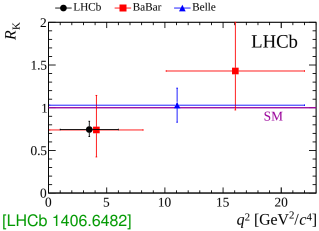
- estimating QED $R_H^{\mu/e}[1,6] = 1.00 \pm 0.01 \quad (H = K, K^*)$ [Bordone/Isidori/Pattori 1605.07633]

Measurement $R_K^{\mu/e}$



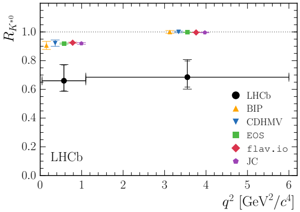
[LHCb 1406.6482]

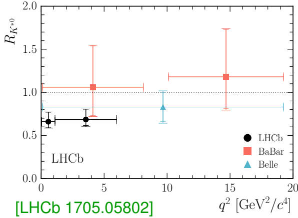
$$R_K^{\mu/e}[1,6] = 0.745^{+0.090}_{-0.074} \pm 0.036$$

correponds to tension $2.6\,\sigma$

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

[Babar 1204.3933, Belle 0904.0770]





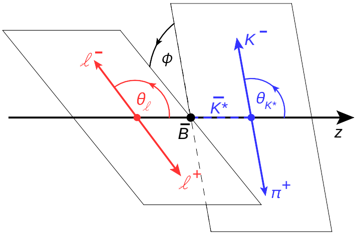
[LHCb 1705.05802]

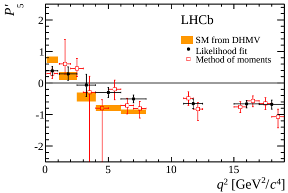
$$R_{K^*}^{\mu/e}[0.045, 1.1] = 0.66^{+0.11}_{-0.07} \pm 0.03 \qquad 2.2\,\sigma$$

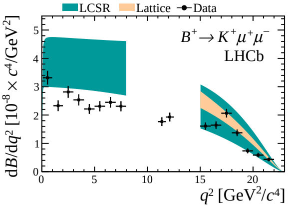
$$R_{K^*}^{\mu/e}[1.1, 6.0] = 0.69^{+0.11}_{-0.07} \pm 0.05 \qquad 2.4\,\sigma$$

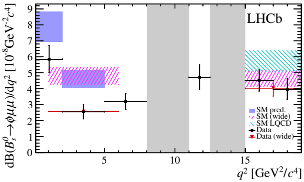
Tensions in angular distribution $B \to K^* \mu\bar{\mu}$ and rates

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









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

[LHCb 1512.04442, Belle 1612.05014]

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

[LHCb 1403.8044]

data below SM prediction

$Br(B_s \to \phi\mu\bar{\mu})$

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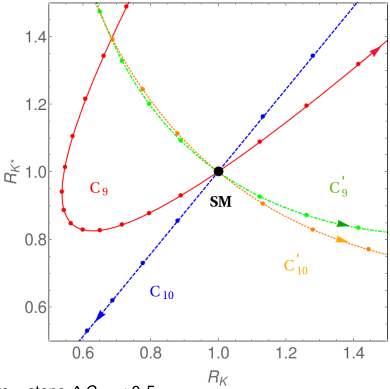
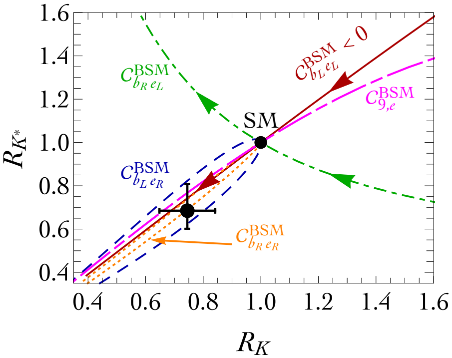
modifications of $\mathcal{C}^{\mu}_{9,9',10,10'}$ **and/or** $\mathcal{C}^{e}_{9,9',10,10'}$

[D'Amico et al. 1704.05438]

[Geng et al. 1704.05446]



New physics in e



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

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

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

[Altmannshofer/Stangl/Straub 1704.05435]

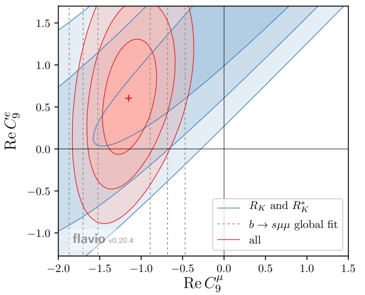
Fit R_K and R_{K^*} for various C_i^ℓ,

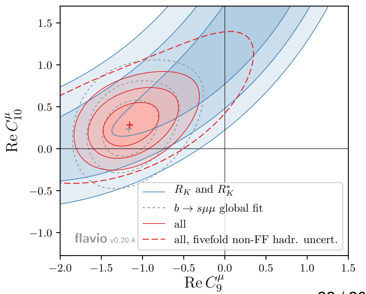
- include $D_{P'_{4,5}}$ measurement [Belle 1612.05014]
- chirality-flipped C_i' disfavored
- no preference of any $\ell = e$ or $\ell = \mu$
- compatible with global $b \to s\mu\bar{\mu}$ anomalies

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

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





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)	$[\mathcal{O}_{\ell q}^{(3)}]_{klij} = [\bar{\ell}_L^k \gamma_\mu \sigma^a \ell_L^l][\bar{q}_L^i \gamma^\mu \sigma^a q_L^j]$
$b \to s\ell\bar{\ell}$	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]

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

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

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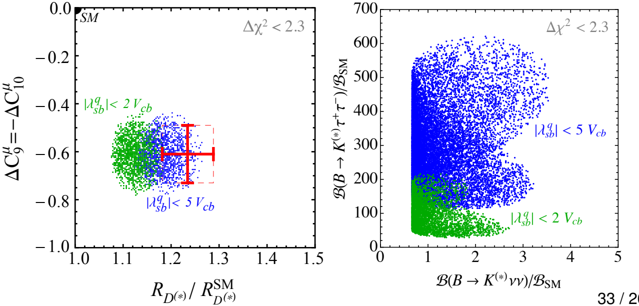
Fit works including

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

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

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

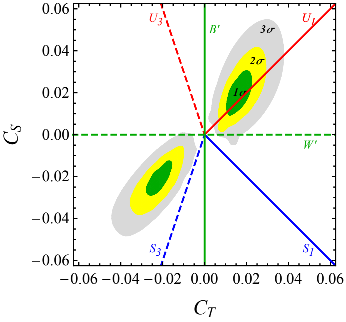
($\mu_{\rm NP}$ = 2 TeV) [Buttazzo/Greljo/Isidori/Marzocca 1706.07808]



NP models

see "definition" of A- & B-type models [Hooman Davoudiasl, talk @ KEK pheno WS 2018]

- **"A-type models"** (MSSM etc.) usually predict $C_9 \ll C_{10}$ (modified Z-penguin)
  $\Rightarrow$ contradict global fits $C_9 \sim -C_{10}$
- **"B-type 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 [too many to mention]
  $\Rightarrow$ 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)

Hadronic contribution to $b \to s\ell\bar{\ell}$

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

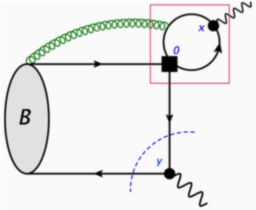
- LC expansion of charm propagator yields [Balitsky/Braun 1989]

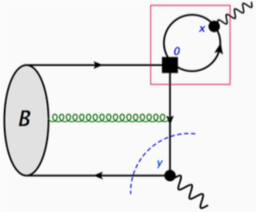
$$\sim \left(\frac{C_1}{3} + C_2\right) g(q^2, m_c^2)\,[\bar{s}\,\Gamma\, b] \quad \leftarrow \text{recover pert. 1-loop}$$

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

calculate matrix element with LCSR

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





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

  !!! 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
  $|z| < 0.52$ for $-7\,\text{GeV}^2 \leq q^2 \leq 14\,\text{GeV}^2$

- 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?

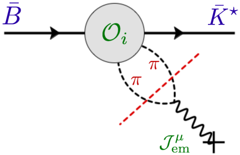
- including $B \to K^* \ell\bar{\ell}$ data the z^n, $n \geq 3$ can be tested, hopefully less relevant

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



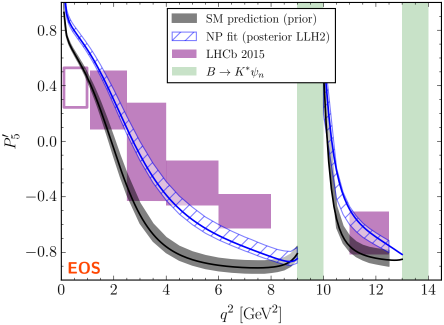
$\Rightarrow$ Current precision of data too limitied to be sensitive to this effect

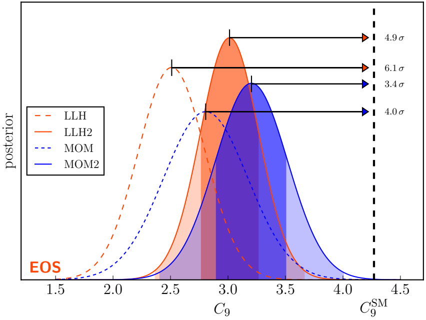
SM predictions + Fit including $B \to K^* \mu\bar{\mu}$ data

[CB/Chrzaszcz/van Dyk/Virto 1707.07305]

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'

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

[work in progress]

⇒ 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
  ⇒ extend the z expansion to $N = 3$ (z^3)
- generalize parametrization to account for small effects from light-hadron cut