GLOBAL FITS and CHARM

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Instant workshop on B anomalies, CERN – May 18, 2017

Based on :

Descotes-Genon, Matias, Virto, 1307.5683 [hep-ph]

Descotes-Genon, Hofer, Matias, Virto, 1510.04239 [hep-ph]

Capdevila, Crivellin, Descotes-Genon, Matias, Virto, 1704.05672 [hep-ph]

Bobeth, Chrzaszcz, van Dyk, Virto, 1?xx.xxxxx [hep-ph]

1. GLOBAL FITS

Descotes-Genon, Matias, Virto, 1307.5683 [hep-ph]

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Capdevila, Crivellin, Descotes-Genon, Matias, Virto, 1704.05672 [hep-ph]

:: Anomalies in $b \to s$ Transitions

Most prominent deviations (out of $\sim$ 170 observables):

Observable	Experiment	Standard Model	Pull (σ)
$\langle P_5' \rangle_{[4,6]}$	-0.30 ± 0.16	-0.82 ± 0.08	-2.9
$\langle P_5' \rangle_{[6,8]}$	-0.51 ± 0.12	-0.94 ± 0.08	-2.9
$R_K^{[1,6]}$	$0.745^{+0.097}_{-0.082}$	1.00 ± 0.01	$+2.6$
$R_{K^*}^{[0.045,1.1]}$	$0.66^{+0.113}_{-0.074}$	0.92 ± 0.02	$+2.3$
$R_{K^*}^{[1.1,6]}$	$0.685^{+0.122}_{-0.083}$	1.00 ± 0.01	$+2.6$
$\mathcal{B}^{[2,5]}_{B_s \to \phi \mu^+ \mu^-}$	0.77 ± 0.14	1.55 ± 0.33	$+2.2$
$\mathcal{B}^{[5,8]}_{B_s \to \phi \mu^+ \mu^-}$	0.96 ± 0.15	1.88 ± 0.39	$+2.2$

Questions:

1. Are these anomalies just "statistics"?
2. If not: Do these anomalies make sense?
3. If yes: What do we learn from them?

:: We **need** Global Fits

Q On 175 observables one expects several 2-sigma deviations.
Is this what is happening here?

A Not very likely, since p-value(SM) $\simeq$ 15%

Q Is a bad SM fit an indication of New Physics?

A Not necessarily.
It could be an indication that measurements and/or predictions are "wrong".
We need an alternative hypothesis that fits well.

Q I will only be convinced if one observable deviates 5σ,
not by adding 2-sigma tensions.

A On the contrary! (It would probably not make sense anyway).

Shopping list:

- A poor SM fit
- At least one "BSM" scenario with a good fit
- A large SM pull in the comparison of BSM to SM.

:: Effective Theory for $b \to s$ Transitions

For $\Lambda_{\rm EW}, \Lambda_{\rm NP} \gg M_B$: General model-independent parametrization of NP :

$$\mathcal{L}_W = \mathcal{L}_{\rm QCD} + \mathcal{L}_{\rm QED} + \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^\star \sum_i \mathcal{C}_i(\mu)\, \mathcal{O}_i(\mu)$$

$$\mathcal{O}_1 = (\bar{c}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_L c) \qquad \mathcal{O}_2 = (\bar{c}\gamma_\mu P_L T^a b)(\bar{s}\gamma^\mu P_L T^a c)$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \qquad \mathcal{O}_{7'} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu}$$

$$\mathcal{O}_{9\ell} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{9'\ell} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10\ell} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \qquad \mathcal{O}_{10'\ell} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

SM contributions to $\mathcal{C}_i(\mu_b)$ known to NNLL Bobeth, Misiak, Urban '99; Misiak, Steinhauser '04, Gorbahn, Haisch '04; Gorbahn, Haisch, Misiak '05; Czakon, Haisch, Misiak '06

$$\mathcal{C}_{7\rm eff}^{\rm SM} = -0.3,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3,\ \mathcal{C}_1^{\rm SM} = 1.1,\ \mathcal{C}_2^{\rm SM} = -0.4,\ \mathcal{C}_{\rm rest}^{\rm SM} \lesssim 10^{-2}$$

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* Important operators in Part 1 $\qquad$ * Important operators in Part 2

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:: Constraining Effective coefficients

- Inclusive
  - $B \to X_s\gamma$ (BR) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_{1,2}$
  - $B \to X_s\ell^+\ell^-$ (dBR/dq^2) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{1,2}$
- Exclusive leptonic
  - $B_s \to \ell^+\ell^-$ (BR) .... $\mathcal{C}_{10}^{(\prime)}$
- Exclusive radiative/semileptonic
  - $B \to K^*\gamma$ (BR, S, A_I) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_{1,2}$
  - $B \to K\ell^+\ell^-$ (dBR/dq^2) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{1,2}$
  - $B \to K^*\ell^+\ell^-$ (dBR/dq^2, Angular Observables) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{1,2}$
  - $B_s \to \phi\ell^+\ell^-$ (dBR/dq^2, Angular Observables) .... $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$, $\mathcal{C}_{1,2}$

Exclusive decay modes have huge weight in fits.

:: Global Fit 2015

Descotes-Genon, Hofer, Matias, Virto 2015

All include $B \to X_s\gamma$, $B \to K^*\gamma$, $B_s \to \mu^+\mu^-$, $B \to X_s\mu^+\mu^-$ by default.

- **Fit 1 (Canonical): $B_{(s)} \to (K^{(*)}, \phi)\mu^+\mu^-$, BR's and P_i's, All q^2** (91 obs)

- **Fit 2**: Branching Ratios only (27 obs)
- **Fit 3**: P_i Angular Observables only (64 obs)
- **Fit 4**: S_i Angular Observables only (64 obs)

- **Fit 5**: $B \to K\mu^+\mu^-$ only (14 obs)
- **Fit 6**: $B \to K^*\mu^+\mu^-$ only (57 obs)
- **Fit 7**: $B_s \to \phi\mu^+\mu^-$ only (20 obs)

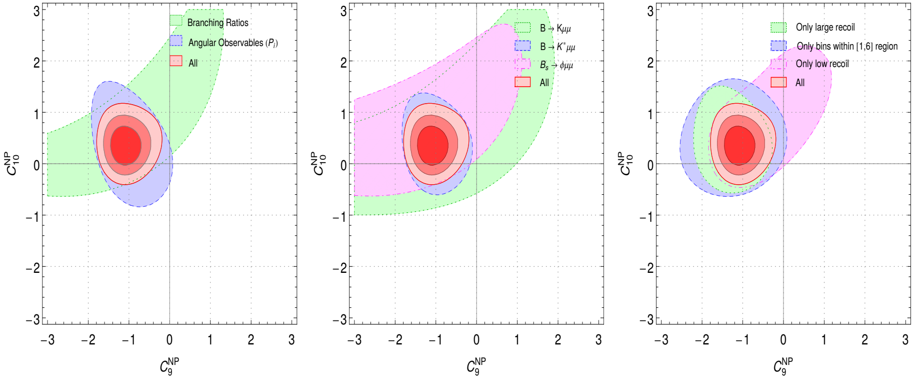
- **Fit 8**: Large Recoil only (74 obs)
- **Fit 9**: Low Recoil only (17 obs)
- **Fit 10**: Only bins within [1,6] GeV^2 (39 obs)
- **Fits 11**: Bin-by-bin analysis.

- **Fit 12**: Full form factor approach [a la ABSZ] (91 obs)
- **Fit 13**: Enhanced Power Corrections (91 obs)
- **Fit 14**: Enhanced Charm loop effect (91 obs)

:: Consistency of different fits

Descotes-Genon, Hofer, Matias, Virto 2015

▷ 3σ constraints, always including $b \to s\gamma$ and inclusive.



▷ Good consistency between BRs and Angular observables (P_i's dominate).

▷ Good consistency between different modes ($B \to K^\star$ dominates).

▷ Good consistency between different q^2 regions (Large-R dominates, [1,6] bulk).

▷ Remember: Quite different theory issues in each case!

:: Update 2017

Capdevila, Crivellin, Descotes-Genon, Matias, Virto 2017

- LHCb : Update for $d\mathcal{B}(B^0 \to K^{\star 0}\mu^+\mu^-)$ (reduction of about 20% in magnitude).
- Belle : Isospin-averaged but lepton-flavour dependent $P'^{\,e,\mu}_{4,5}(B \to K^\star \ell\ell)$.
- ATLAS : P_1, $P'_{4,5,6,8}$ in $B^0 \to K^{\star 0}\mu^+\mu^-$ as well as F_L in the large recoil region.
- CMS : P_1 and P'_5 in $B^0 \to K^{\star 0}\mu^+\mu^-$, at large recoil and [16,19] GeV^2. F_L and A_{FB} from the 2015 analysis and also the measurements at 7 TeV in 2013.
- LHCb : $R_{K^\star}$ in the two bins.

We perform 2 types of fits:

- All data (175 measurements)
- LFUV fit: R_K, $R_{K^\star}$, $Q_{4,5}$ and $b \to s\gamma$ (17 measurements)

:: 6D hypothesis

Capdevila, Crivellin, Descotes-Genon, Matias, Virto 2017

▷ All 6 WCs free (but real).

Coefficient	Best Fit	1σ	2σ
$\mathcal{C}_7^{\rm NP}$	$+0.02$	$[-0.01,+0.05]$	$[-0.03,+0.07]$
$\mathcal{C}_9^{\rm NP}$	-1.12	$[-1.34,-0.85]$	$[-1.51,-0.61]$
$\mathcal{C}_{10}^{\rm NP}$	$+0.33$	$[+0.09,+0.59]$	$[-0.10,+0.80]$
$\mathcal{C}_{7'}^{\rm NP}$	$+0.03$	$[-0.00,+0.06]$	$[-0.02,+0.08]$
$\mathcal{C}_{9'}^{\rm NP}$	$+0.59$	$[+0.01,+1.12]$	$[-0.50,+1.56]$
$\mathcal{C}_{10'}^{\rm NP}$	$+0.07$	$[-0.23,+0.37]$	$[-0.50,+0.64]$

▷ $\mathcal{C}_9$ consistent with SM only above $3\,\sigma$ Descotes-Genon, Matias, Virto 1307.5683

▷ All others consistent with the SM at $1\,\sigma$, except for $\mathcal{C}_9'$,$\mathcal{C}_{10}'$ at $2\,\sigma$.

▷ Pull_{SM} for the 6D fit is $5.0\,\sigma$ (compared to $3.6\,\sigma$ in 2015).

:: 1D hypotheses

Capdevila, Crivellin, Descotes-Genon, Matias, Virto 2017

All	Best fit	$2\ \sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	-1.10	$[-1.43, -0.74]$	5.7	72
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	-0.61	$[-0.87, -0.36]$	5.2	61
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}'_{9\mu}$	-1.01	$[-1.33, -0.65]$	5.4	66
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -3\mathcal{C}_{9e}^{\mathrm{NP}}$	-1.06	[-1.39,-0.71]	5.8	74

LFUV	Best fit	$2\ \sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	-1.76	$[-3.04, -0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	-0.66	$[-1.04, -0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}'_{9\mu}$	-1.64	$[-2.52, -0.49]$	3.2	31
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -3\mathcal{C}_{9e}^{\mathrm{NP}}$	-1.35	$[-2.38, -0.59]$	4.0	71

$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}'_{9\mu}$ implies $R_K \simeq 1$

$\mathcal{C}_{9\mu} = \mathcal{C}_{9e}$ has a pull of $3.3\ \sigma$

:: 2D hypotheses

Capdevila, Crivellin, Descotes-Genon, Matias, Virto 2017

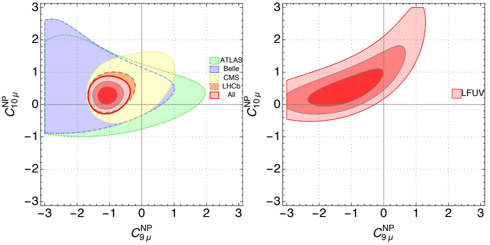
	All			LFUV		
2D Hyp.	Best fit	Pull_{SM}	p-value	Best fit	Pull_{SM}	p-value
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$	(-1.17,0.15)	5.5	74	(-1.13,0.40)	3.7	75
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{7}')$	(-1.05,0.02)	5.5	73	(-1.75,-0.04)	3.6	66
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu})$	(-1.09,0.45)	5.6	75	(-2.11,0.83)	3.7	73
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10'\mu})$	(-1.10,-0.19)	5.6	76	(-2.43,-0.54)	3.9	85
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9e}^{\text{NP}})$	(-0.97,0.50)	5.4	72	(-1.09,0.66)	3.5	65
Hyp. 1	(-1.08,0.33)	5.6	77	(-1.74,0.53)	3.8	77
Hyp. 2	(-1.00, 0.15)	4.9	61	(-1.89,0.27)	3.1	39
Hyp. 3	(-0.65,-0.13)	4.9	61	(0.58,2.53)	3.7	73
Hyp. 4	(-0.65,0.21)	4.8	59	(-0.68,0.28)	3.7	72

Hyp. 1: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = \mathcal{C}_{10'\mu})$

Hyp. 2: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{\text{NP}} = -\mathcal{C}_{10'\mu})$

Hyp. 3: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = \mathcal{C}_{10'\mu})$

Hyp. 4: $(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$



:: $SU(2) \times U(1)$ Gauge Invariance

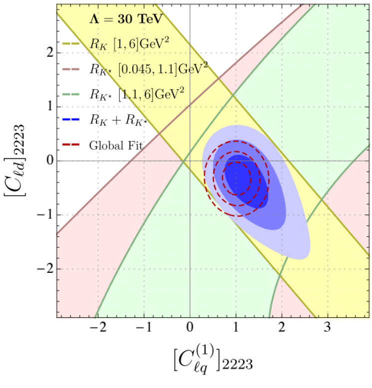
Celis, Fuentes, Vicente, Virto 2017

$$\mathcal{C}_{9a}^{\rm NP} = \frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ [\tilde{\mathcal{C}}_{\ell q}^{(1)}]_{aa23} + [\tilde{\mathcal{C}}_{\ell q}^{(3)}]_{aa23} + [\tilde{\mathcal{C}}_{qe}]_{23aa} \right\},$$

$$\mathcal{C}_{10a}^{\rm NP} = -\frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ [\tilde{\mathcal{C}}_{\ell q}^{(1)}]_{aa23} + [\tilde{\mathcal{C}}_{\ell q}^{(3)}]_{aa23} - [\tilde{\mathcal{C}}_{qe}]_{23aa} \right\}$$

$$\mathcal{C}'_{9a} = \frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ [\tilde{\mathcal{C}}_{\ell d}]_{aa23} + [\tilde{\mathcal{C}}_{ed}]_{aa23} \right\},$$

$$\mathcal{C}'_{10a} = -\frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ [\tilde{\mathcal{C}}_{\ell d}]_{aa23} - [\tilde{\mathcal{C}}_{ed}]_{aa23} \right\}. \quad (6$$



SMEFT operator	Definition	Matching	Order
$[Q_{\ell q}^{(1)}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \ell_a)\,(\bar{q}_2 \gamma^\mu q_3)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{\ell q}^{(3)}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \tau^I \ell_a)\,(\bar{q}_2 \gamma^\mu \tau^I q_3)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{qe}]_{23aa}$	$(\bar{q}_2 \gamma_\mu q_3)\,(\bar{e}_a \gamma^\mu e_a)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{\ell d}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \ell_a)\,(\bar{d}_2 \gamma^\mu d_3)$	$\mathcal{O}'_{9,10}$	Tree
$[Q_{ed}]_{aa23}$	$(\bar{e}_a \gamma_\mu e_a)\,(\bar{d}_2 \gamma^\mu d_3)$	$\mathcal{O}'_{9,10}$	Tree
$[Q_{\varphi \ell}^{(1)}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)\,(\bar{\ell}_a \gamma^\mu \ell_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\varphi \ell}^{(3)}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi\right)\,(\bar{\ell}_a \gamma^\mu \tau^I \ell_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\ell u}]_{aa33}$	$(\bar{\ell}_a \gamma_\mu \ell_a)\,(\bar{u}_3 \gamma^\mu u_3)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\varphi e}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)\,(\bar{e}_a \gamma^\mu e_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{eu}]_{aa33}$	$(\bar{e}_a \gamma_\mu e_a)\,(\bar{u}_3 \gamma^\mu u_3)$	$\mathcal{O}_{9,10}$	1-loop

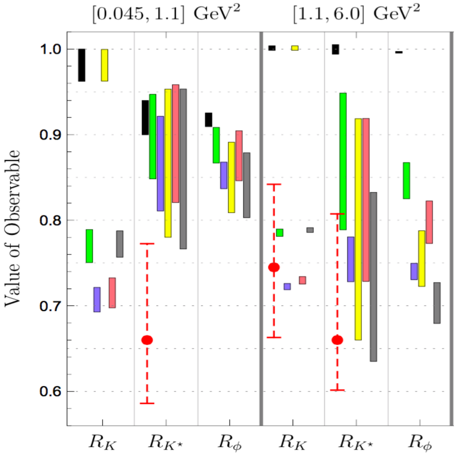
Loop effects:

$$[\mathcal{C}_{\ell q}^{(1)}(\mu_{\rm EW})]_{aa23} = [\mathcal{C}_{\ell q}^{(1)}(\Lambda)]_{aa23} - \frac{y_t^2 \lambda_t^{sb}}{16\pi^2} \log\left(\frac{\Lambda}{\mu_{\rm EW}}\right) \left([\mathcal{C}_{\varphi \ell}^{(1)}(\Lambda)]_{aa} - [\mathcal{C}_{\ell u}(\Lambda)]_{aa33}\right)$$

$$\mathcal{C}_{9\mu}^{\rm NP} \simeq \frac{1}{s_W^2} \frac{v^2}{\Lambda^2} \frac{x_t}{8} [\tilde{\mathcal{C}}_{\ell u}(\Lambda)]_{2233} \left[\log\left(\frac{\Lambda}{M_W}\right) + I_0(x_t)\right]$$

$\rightarrow \mathcal{C}_{\ell u}$ is a viable posibility

:: Hadronic uncertainties in LFNU observables



- In the presence of LFUV (SM or NP), hadronic uncertainties reappear.
- First bin of R_{K^*} not so bad once hadronic uncertainties are considered.
- "Clean" observables in the presence of LFUV have been proposed, too.

  Capdevila, Descotes-Genon, Matias, Virto 2016

  Serra, Coutinho, van Dyk 2016

:: Summary I

Scenarios with $\mathcal{C}_{9\mu}^{\rm NP} \sim -1$ give **substantially improved fits** for

- ▷ $B \to K\mu\mu$, $B \to K^*\mu\mu$ and $B_s \to \Phi\mu\mu$
- ▷ BRs and angular observables (including P_5')
- ▷ Low q^2 and large q^2
- ▷ LFNU: R_K, $R_{K^\star}$ and Q_5

Other scenarios also motivated but all with $\mathcal{C}_{9\mu}^{\rm NP}$.

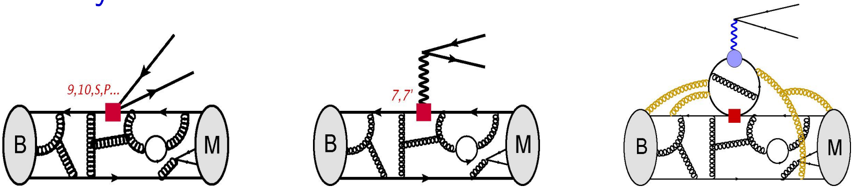
2017 updates increase the significance of the $b \to s$ anomalies.

- Global SM pulls of $\sim 5\sigma$ in many fits, including 6D fit.
- SM p-value is 14.6% (All) and 4.4% (LFUV)

2. A Systematic Approach to CHARM

Bobeth, Chrzaszcz, van Dyk, Virto (w.i.p.)

:: Theory calculation for $B \to M\ell^+\ell^-$



$$\mathcal{M}_\lambda = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[(\mathcal{A}_\lambda^\mu + \mathcal{H}_\lambda^\mu)\ \bar{u}_\ell \gamma_\mu v_\ell + \mathcal{B}_\lambda^\mu\ \bar{u}_\ell \gamma_\mu \gamma_5 v_\ell \right] + \mathcal{O}(\alpha^2)$$

Local:

$$\mathcal{A}_\lambda^\mu = -\frac{2 m_b q_\nu}{q^2} \mathcal{C}_7 \langle M_\lambda | \bar{s} \sigma^{\mu\nu} P_R b | B \rangle + \mathcal{C}_9 \langle M_\lambda | \bar{s} \gamma^\mu P_L b | B \rangle$$

$$\mathcal{B}_\lambda^\mu = \mathcal{C}_{10} \langle M_\lambda | \bar{s} \gamma^\mu P_L b | B \rangle$$

Non-Local:

$$\mathcal{H}_\lambda^\mu = -\frac{16 i \pi^2}{q^2} \sum_{i=1..6,8} \mathcal{C}_i \int dx^4 e^{iq\cdot x} \langle M_\lambda | T\{\mathcal{J}_{\rm em}^\mu(x), \mathcal{O}_i(0)\} | B \rangle$$

Two theory issues:

1. **Form Factors** (LCSRs, LQCD, symmetry relations . . .)
2. **Hadronic contribution** (SCET/QCDF, OPE, LCOPE . . . **THIS TALK**)

:: Hadronic correlator : Current approaches

- ▷ QCD-Factorization at $0 < q^2 \ll M^2_{J/Psi}$ Beneke, Feldmann, Seidel
  - Based on large-energy limit, bottleneck is power corrections.
  - Used in the region where light quarks can go on-shell.
- ▷ LCOPE at $q^2 < 0$ + LCSR for matrix elements + Dispersion relation ($\to q^2 > 0$) Khodjamirian, Mannel, Pivovarov, Wang, Rusov.
  - Systematic. Allows to compute power corrections.
  - LCOPE needs perturbative calculation at LCSR $q^2 < 0$. Difficult for NLO.
  - Assumes local duality for intermediate states in s-channel.
- ▷ Fit to data Ciuchini et al., Chovanova et al.
  - Not predictive !
  - Ad-hoc parametrization, not motivated.
  - Embedding New Physics can use "Wilks' test (but inconclusive).
- ▷ "Low-recoil" OPE at $M^2_{\psi(2S)} < q^2 < M^2_B$ Grinstein, Pirjol , Hiller, Bobeth, van Dyk
  - Must integrate over large region to "smear" spectral density.
  - Can calculate power corrections, but HMEs not known.
- ▷ Factorization Approximation + data Lyon, Zwicky, Brass, Hiller, Nisandzic
  - "Vaccuum polarization" contribution completely included.
  - Non-factorizable effects must be introduced separately.

:: Hadronic correlator : Decomposition

Bobeth, Chrzaszcz, van Dyk, Virto

$$\mathcal{H}^\mu(q,k) \equiv i \int \mathrm{d}^4x\ e^{iq\cdot x}\ \langle \bar{K}^*(k,\eta)|T\{\bar{c}\gamma^\mu c(x), \mathcal{C}_1\mathcal{O}_1 + \mathcal{C}_2\mathcal{O}_2(0)\}|\bar{B}(p)\rangle$$

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

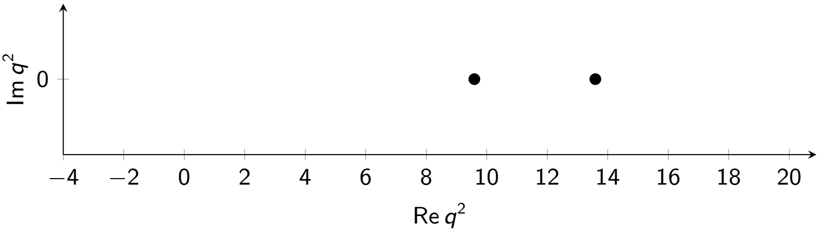
- $S_\lambda^{\alpha\mu}$ – basis of Lorentz structures (carefully chosen)
- $\mathcal{H}_\lambda$ – Lorentz invariant correlation functions
- λ – polarization states ($\perp$, $\parallel$, 0)

The idea :

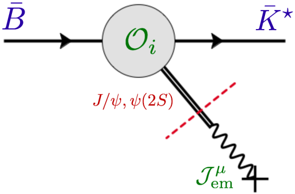
- Understand analytic structure of $\mathcal{H}_\lambda(q^2)$ to write a general parametrisation consistent with QCD.
- Use **suitable** experimental information to constrain the correlator.
- Use theory to constrain the correlator in **suitable** kinematic points.

:: Hadronic correlator : Analytic structure

Bobeth, Chrzaszcz, van Dyk, Virto



- narrow charmonia, assumed to be stable



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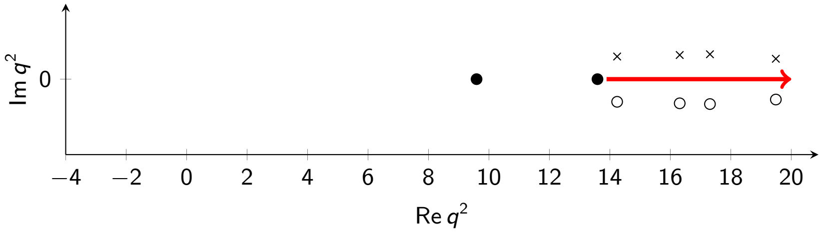
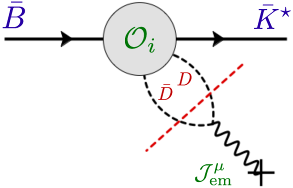


- ● narrow charmonia, assumed to be stable
- red branch cut from $D\bar{D}$ production
- ○ broad charmonia, decaying to $D\bar{D}$
- × potential mirror poles



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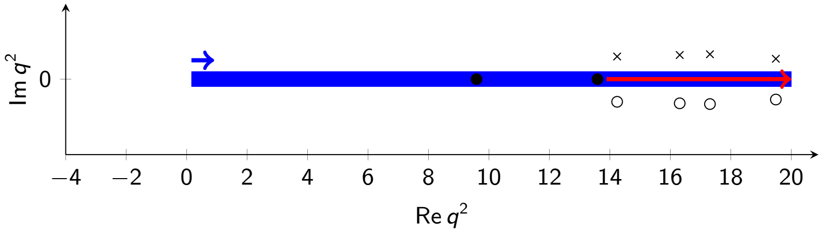
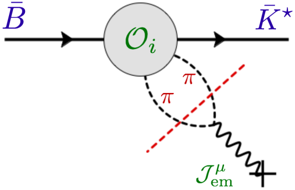


- ● narrow charmonia, assumed to be stable
- red branch cut from $D\bar{D}$ production
- ○ broad charmonia, decaying to $D\bar{D}$
- × potential mirror poles
- blue branch cut from light hadrons



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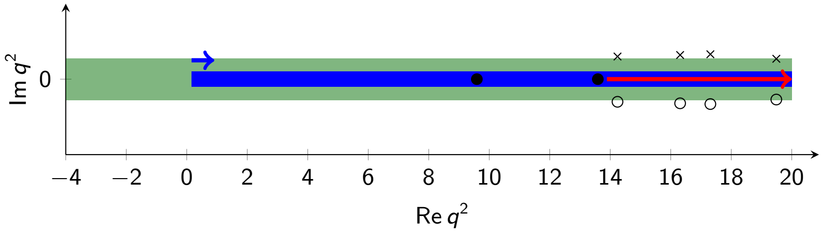
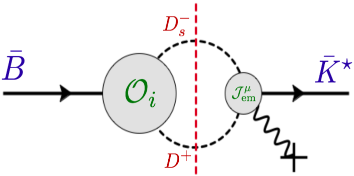


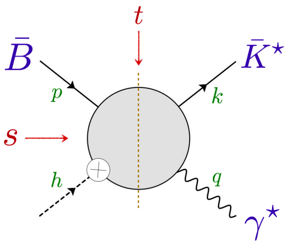
- ● narrow charmonia, assumed to be stable
- red branch cut from $D\bar{D}$ production
- ○ broad charmonia, decaying to $D\bar{D}$
- × potential mirror poles
- blue branch cut from light hadrons
- green q^2-dep. imaginary due to branch cut in p^2

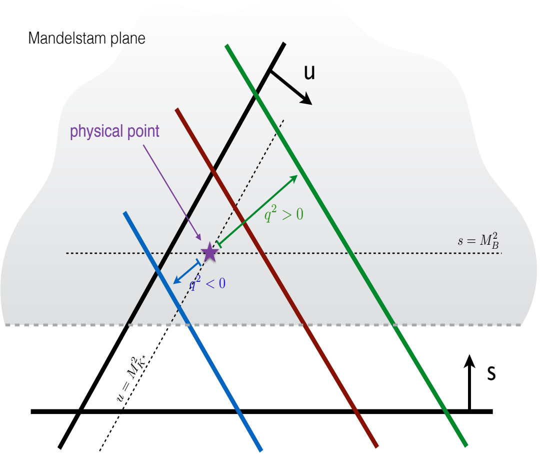


:: Understanding the p^2 cut

Bobeth, Chrzaszcz, van Dyk, Virto

Trick :	Add spurious momentum h to $\mathcal{O}_i$
	Recover physical kinematics as $h \to 0$





- $s \sim p^2$ independent of $t \sim q^2$.
- Cut in p^2 does not translate into cut in q^2
- Two correlators:

$$\mathcal{H}_\lambda(q^2) \to \mathcal{H}_\lambda^{\text{real}}(q^2) + i\,\mathcal{H}_\lambda^{\text{imag}}(q^2)$$

- Both $\mathcal{H}_\lambda^{\text{real}}(q^2)$ and $\mathcal{H}_\lambda^{\text{imag}}(q^2)$ are analytic at $q^2 \leq 0$
- Both $\mathcal{H}_\lambda^{\text{real}}(q^2)$ and $\mathcal{H}_\lambda^{\text{imag}}(q^2)$ have branch cuts at $q^2 > 0$

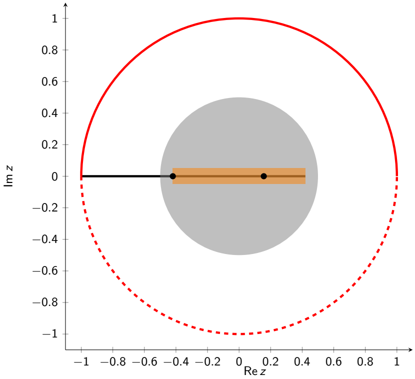
:: Parametrization A : $J/\psi, \psi(2s)$ poles + $D\bar{D}$ cut

Bobeth, Chrzaszcz, van Dyk, Virto

Motivated by famous "z-parametrization" of form factors. Boyd et al '94, Bourelly et al '08

1. extract the poles

$$\hat{\mathcal{H}}_\lambda(q^2) = (q^2 - M^2_{J/\psi})(q^2 - M^2_{\psi(2S)})\,\mathcal{H}_\lambda(q^2)$$



2. $\hat{\mathcal{H}}_\lambda(q^2)$ is analytic except for $D\bar{D}$ cut.
3. Perform conformal mapping $q^2 \mapsto z(q^2)$.
4. $\hat{\mathcal{H}}_\lambda(z)$ analytic within unit circle.
5. Taylor expand $\hat{\mathcal{H}}_\lambda(z)$ around $z = 0$.
6. Good convergence expected since $|z| < 0.42$ for $-5\,\mathrm{GeV}^2 \leq q^2 \leq 14\mathrm{GeV}^2$

:: Experimental constraints on the correlator

Bobeth, Chrzaszcz, van Dyk, Virto

The correlators $\mathcal{H}_\lambda$ can be related to observables in the decays $B \to K^* J/\psi, K^*\psi(2S)$

- Independent of short-distance contributions ($\mathcal{C}_7$, $\mathcal{C}_9$, etc) in $B \to K^*\{\gamma, \mu^+\mu^-\}$
- Important constraints at $\boldsymbol{q^2} \simeq \mathbf{9}\,\text{GeV}^2$ and $\boldsymbol{q^2} \simeq \mathbf{14}\,\text{GeV}^2$.

Details:

- residues of the correlator can be expressed in terms of $B \to K^*\psi$ amplitudes.
  Khodjamirian et. al. 2010
- $\mathcal{B}$ and 4 angular observables measured in $B \to K^* J/\psi$ and $B \to K^*\psi(2S)$
  LHCb 2013, BaBar 2007
- Allows to constrain all moduli and two relative phases of the amplitudes, and therefore of the residues of the correlator.

:: Theory constraints on the correlator

Bobeth, Chrzaszcz, van Dyk, Virto

The correlator **can be calculated at $q^2 < 0$ reliably** by means of a light-cone OPE

Khodjamirian et al. 2010

Using $\mathcal{H}_\perp(q^2)$ as an example:

$$\mathcal{H}_\perp(q^2) = \# \times g(q^2, m_c^2)\ \mathcal{F}_\perp(q^2)\ +\ \# \times \widetilde{V}_1(q^2)\ +\ \mathrm{NLO}_{\alpha_s}$$

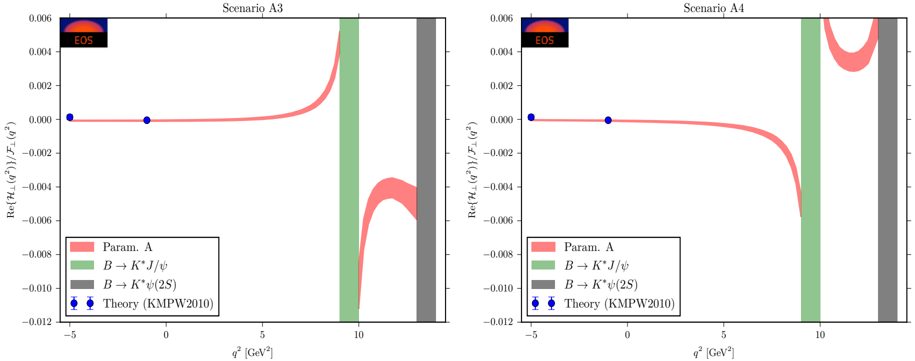
- first term is usual form-factor-like contribution
- second term arises from soft-gluon effects only
- third term arises from NLO corrections (produces p^2 cut !!)

We use this to constrain the correlators at $\boldsymbol{q^2 = -1}$ GeV^2 and $\boldsymbol{q^2 = -5}$ GeV^2.

:: Results Parametrization A Preliminary

Bobeth, Chrzaszcz, van Dyk, Virto

Results for $\mathrm{Re}(\mathcal{H}_\perp/\mathcal{F}_\perp)$ **:**



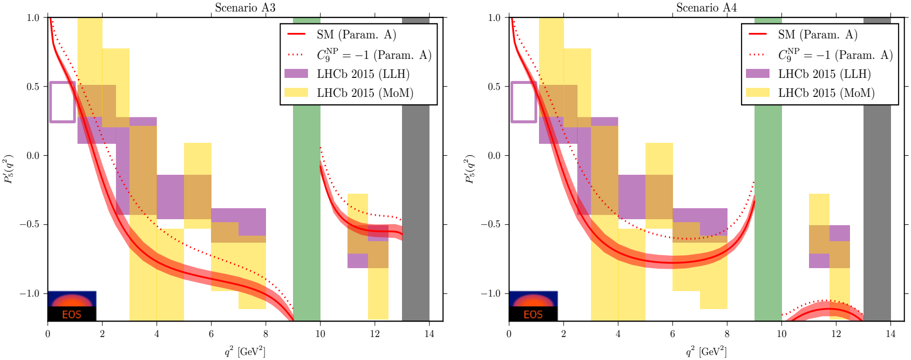
Discrete ambiguity in phases of the residues : (only two shown)

Left : $\phi_{J/\psi} = \pi\ ,\ \phi_{\psi(2S)} = 0$ **Right :** $\phi_{J/\psi} = \phi_{\psi(2S)} = \pi$

:: Results Parametrization A Preliminary

Bobeth, Chrzaszcz, van Dyk, Virto

SM predictions for P_5'



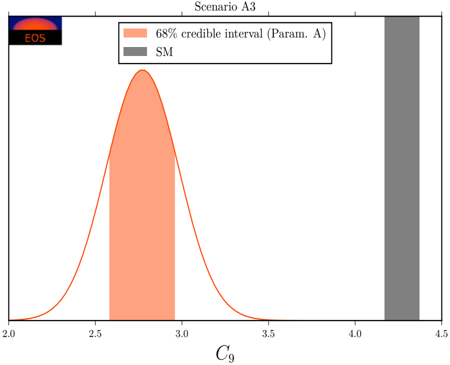
Left : $\phi_{J/\psi} = \pi$, $\phi_{\psi(2S)} = 0$ **Right :** $\phi_{J/\psi} = \phi_{\psi(2S)} = \pi$

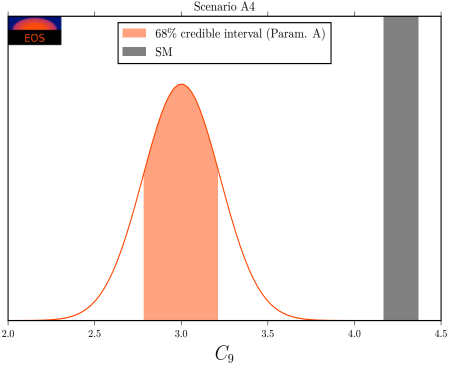
▷ first-time use of inter-resonance bin : **great potential!!**

:: Confronting $B \to K^\star \mu\mu$ data Preliminary

Bobeth, Chrzaszcz, van Dyk, Virto

Global fit to all $B \to K^\star\{\gamma, \mu^+\mu^-, J/\psi, \psi(2S)\}$ data using Parametrization A





Left : $\phi_{J/\psi} = \pi$, $\phi_{\psi(2S)} = 0$

Right : $\phi_{J/\psi} = \phi_{\psi(2S)} = \pi$

:: Summary II

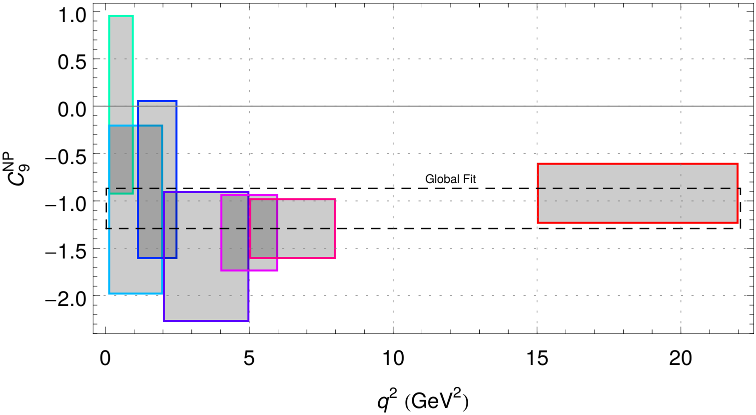
- Systematic framework to access nonlocal correlator
  - First approach to use both theory inputs and experimental constraints in fit
  - Can accommodate existing and future theory results (systematically improvable)
  - Provides model-independent prior predictions for $B \to K^{(*)}\mu^+\mu^-$
  - Can be easily embedded in global fits
- Present data in tension with parametrization A
  - favours NP interpretation with $> 4\sigma$
- Other results not disclosed here: see Bobeth, Chrzaszcz, van Dyk, Virto w.i.p
  - Complex parametrization A : needs analytic NLO Greub, Virto w.i.p.
  - Parametrization B : includes light-hadron cut from ψ decay

Back-up

:: Hadronic correlator: are we missing something?

Descotes-Genon, Hofer, Matias, Virto

$$\rightarrow \mathcal{T}_\mu = -\frac{16 i\pi^2}{q^2} \sum_{i=1..6,8} \mathcal{C}_i \int dx^4 e^{iq\cdot x} \langle M_\lambda | T\{\mathcal{J}_\mu^{\text{em}}(x)\mathcal{O}_i(0)\}|B\rangle \text{ is } q^2\text{-dependent}$$



$\Rightarrow$ No evidence for q^2-dependence $\rightarrow$ Good crosscheck of hadronic contribution!

:: Overview of exp. constraints on Correlator

Bobeth, Chrzaszcz, van Dyk, Virto

name	observables	degrees of freedom	source
$\bar{B} \to \bar{K}^* J/\psi$	$\mathcal{B}$, $F_\perp$, $F_\parallel$, $\delta_\perp$, $\delta_\parallel$	5	BaBar
	$\mathcal{B}$, $F_\perp$, $F_\parallel$, $\delta_\perp$, $\delta_\parallel$	5	Belle
	$\mathcal{B}$, $F_\perp$, F_0, $\delta_\perp$, $\delta_\parallel$	5	CDF
	$\mathcal{B}$	1	CLEO
	$F_\perp$, F_0, $\delta_\perp$, $\delta_\parallel$	4	LHCb
$\bar{B} \to \bar{K}^* \psi(2S)$	$\mathcal{B}$, $F_\perp$, $F_\parallel$, $\delta_\perp$, $\delta_\parallel$	5	BaBar
	$\mathcal{B}$	1	Belle
	$\mathcal{B}$	1	CDF
	$\mathcal{B}$	1	CLEO
$\bar{B} \to \bar{K}^* \gamma$	$\mathcal{B}$	1	CLEO
	$\mathcal{B}$, $S_{K^*\gamma}$	1	Belle
	$\mathcal{B}$, $S_{K^*\gamma}$	1	BaBar
$\bar{B} \to \bar{K}^* \mu^+\mu^-$	$\mathcal{B}$, F_L, S_3, S_4, S_5, $A_{\rm FB}$, S_7, S_8, S_9	4×9	LHCb
$\bar{B} \to \bar{K}^* \mu^+\mu^-$ "inter-resonance"	$\mathcal{B}$, F_L, S_3, S_4, S_5, $A_{\rm FB}$, S_7, S_8, S_9	9	LHCb

:: Anomaly patterns

		R_K	$\langle P_5' \rangle_{[4,6],[6,8]}$	$BR(B_s \to \phi\mu\mu)$	low recoil BR	Best fit now
$\mathcal{C}_9^{\rm NP}$	+					
	−	✓	✓	✓	✓	X
$\mathcal{C}_{10}^{\rm NP}$	+	✓		✓	✓	X
	−		✓			
$\mathcal{C}_{9'}^{\rm NP}$	+			✓	✓	X
	−	✓	✓			
$\mathcal{C}_{10'}^{\rm NP}$	+	✓	✓			
	−			✓	✓	X

▷ $\mathcal{C}_9 < 0$ consistent with all the anomalies

▷ No consistent and global alternative from long-distance dynamics.

If the (current) exclusive fit is accurate, inclusive $b \to s\ell\ell$ Belle-2 measurements alone have the potential for a NP discovery: