Theory of $b \to s\ell\ell$:

New Physics Fits and Hadronic Contributions

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Current Trends in Flavor Physics – Paris, March 29, 2017

:: 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 this talk.

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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.

:: Outline

The idea is to constrain very well the WCs, compare with the SM and learn about NP.

If it was obvious that **it is not** New Physics, we wouldn't be discussing this so much, so:

1. Review of Fits and Evidence (?) for New Physics

as a motivational starter.

These fits assume NP **only** in $\mathcal{C}^{(\prime)}_{7,9,10}$.
The interesting possibility of NP in $(\bar{s}c)(\bar{c}b)$ will be discussed by **Sebastian Jäger.**

But the problem really is **SM uncertainties**. So:

2. Hadronic contributions

Many issues here will be left for the talk by **Bernat Capdevila.**

Once the anomalies are **interpreted model-independently** we need to figure out **which models** can explain them. So:

3. Model-dependent interpretations – **Not covered in this talk.**

But see talk by **Olcyr Sumensari**.

1. Global Fits and New Physics

:: Chronology of $b \to s\ell\ell$ (last $\sim$ 5 years)

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- ▷ **2017** ATLAS + CMS. **Question marks.....**

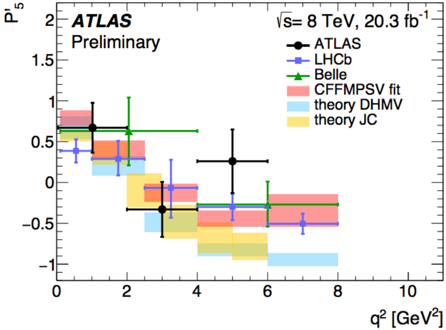
:: Chronology of $b \to s\ell\ell$ (future)

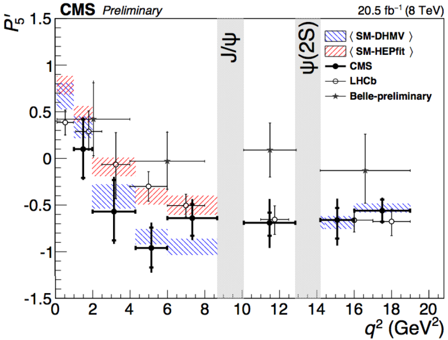
▷ **2017?** LHCb measures $R_{K^\star}$ **Everyone's head explodes.**

:: The P_5' Anomaly

P_5' is an "optimized" angular observable in $B \to K^\star \mu^+ \mu^-$ 1207.2753 [hep-ph]

LHCb 2013 + 2015, Belle 2016 + Recent ATLAS + CMS Moriond 2017 !





Word of caution : CMS results take F_L and S-wave from separate analysis.

But P_5' is not the only observable ....

:: Global Fits to all $b \to s$ data

Descotes-Genon, Hofer, Matias, Virto

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)

:: Canonical Fit: 6D hypotheses

Descotes-Genon, Hofer, Matias, Virto

▷ All 6 WCs free (but real).

Coefficient	1σ	2σ	3σ
$\mathcal{C}_7^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.04]$	$[-0.05, 0.08]$
$\mathcal{C}_9^{\rm NP}$	$[-1.4, -1.0]$	$[-1.7, -0.7]$	$[-2.2, -0.4]$
$\mathcal{C}_{10}^{\rm NP}$	$[-0.0, 0.9]$	$[-0.3, 1.3]$	$[-0.5, 2.0]$
$\mathcal{C}_{7'}^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.06]$	$[-0.06, 0.07]$
$\mathcal{C}_{9'}^{\rm NP}$	$[0.3, 1.8]$	$[-0.5, 2.7]$	$[-1.3, 3.7]$
$\mathcal{C}_{10'}^{\rm NP}$	$[-0.3, 0.9]$	$[-0.7, 1.3]$	$[-1.0, 1.6]$

▷ $\mathcal{C}_9$ consistent with SM only above $3\,\sigma$.

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

▷ Pull_{SM} for the 6D fit is $3.6\,\sigma$.

:: Canonical Fit: 1D hypotheses

Descotes-Genon, Hofer, Matias, Virto

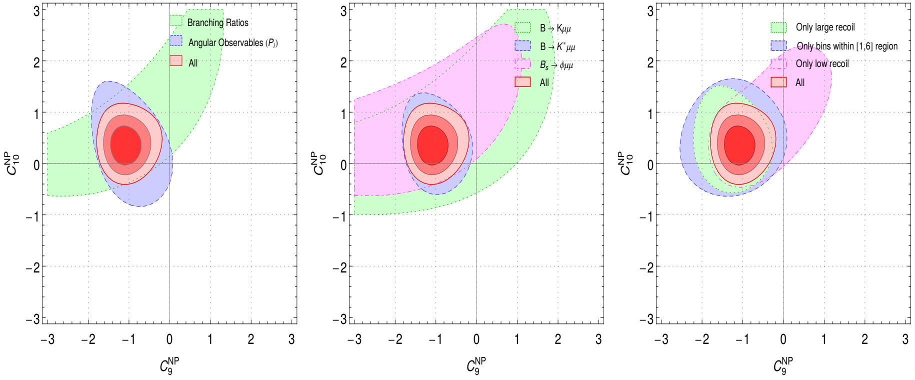
- ▷ Pull$_{\rm SM}$: $\sim \chi^2_{\rm SM} - \chi^2_{\rm min}$ (metrology: how less likely is SM vs. best fit?)
- ▷ p-value: $p(\chi^2_{\rm min}, N_{\rm dof})$ (goodness of fit: is the best fit a good fit?)
- ▷ Contribution $\mathcal{C}_9^{\rm NP} < 0$ always favoured.

Coefficient	Best fit	3σ	Pull$_{\rm SM}$	p-value (%)
SM	–	–	–	16.0
$\mathcal{C}_7^{\rm NP}$	-0.02	$[-0.07, 0.03]$	1.2	17.0
$\boldsymbol{\mathcal{C}_9^{\rm NP}}$	-1.09	$[-1.67, -0.39]$	**4.5**	63.0
$\mathcal{C}_{10}^{\rm NP}$	0.56	$[-0.12, 1.36]$	2.5	25.0
$\mathcal{C}_{7'}^{\rm NP}$	0.02	$[-0.06, 0.09]$	0.6	15.0
$\mathcal{C}_{9'}^{\rm NP}$	0.46	$[-0.36, 1.31]$	1.7	19.0
$\mathcal{C}_{10'}^{\rm NP}$	-0.25	$[-0.82, 0.31]$	1.3	17.0
$\mathcal{C}_9^{\rm NP} = \mathcal{C}_{10}^{\rm NP}$	-0.22	$[-0.74, 0.50]$	1.1	16.0
$\boldsymbol{\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}}$	-0.68	$[-1.22, -0.18]$	**4.2**	56.0
$\mathcal{C}_{9'}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP}$	-0.07	$[-0.86, 0.68]$	0.3	14.0
$\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP}$	0.19	$[-0.17, 0.55]$	1.6	18.0
$\boldsymbol{\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}}$	-1.06	$[-1.60, -0.40]$	**4.8**	72.0

:: Consistency of different fits

Descotes-Genon, Hofer, Matias, Virto

▷ $3\,\sigma$ 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!

:: Other Fits   Altmannshofer, Straub

- ▷ Uses the S_i basis of angular observables in $B \to K^\star \mu\mu$
- ▷ Uses "full form factors" from
  a fit to LCSRs Barucha, Straub, Zwicky and Lattice Bouchard et al, Horgan et al.
- ▷ Uses all data from all experiments, but only 2D fits at most.

Coeff.	best fit	1σ	2σ	$\chi^2_{\rm SM} - \chi^2_{\rm b.f.}$	pull
$C_7^{\rm NP}$	-0.04	$[-0.07, -0.01]$	$[-0.10, 0.02]$	2.0	1.4
C_7'	0.01	$[-0.04, 0.07]$	$[-0.10, 0.12]$	0.1	0.2
$C_9^{\rm NP}$	-1.07	$[-1.32, -0.81]$	$[-1.54, -0.53]$	13.7	3.7
C_9'	0.21	$[-0.04, 0.46]$	$[-0.29, 0.70]$	0.7	0.8
$C_{10}^{\rm NP}$	0.50	$[0.24, 0.78]$	$[-0.01, 1.08]$	3.9	2.0
C_{10}'	-0.16	$[-0.34, 0.02]$	$[-0.52, 0.21]$	0.8	0.9
$C_9^{\rm NP} = C_{10}^{\rm NP}$	-0.22	$[-0.44, 0.03]$	$[-0.64, 0.33]$	0.8	0.9
$C_9^{\rm NP} = -C_{10}^{\rm NP}$	-0.53	$[-0.71, -0.35]$	$[-0.91, -0.18]$	9.8	3.1
$C_9' = C_{10}'$	-0.10	$[-0.36, 0.17]$	$[-0.64, 0.43]$	0.1	0.4
$C_9' = -C_{10}'$	0.11	$[-0.01, 0.22]$	$[-0.12, 0.33]$	0.9	0.9

:: Other Fits

Hurth, Mahmoudi, Neshatpour

- ▷ Uses the S_i basis of angular observables in $B \to K^\star \mu\mu$
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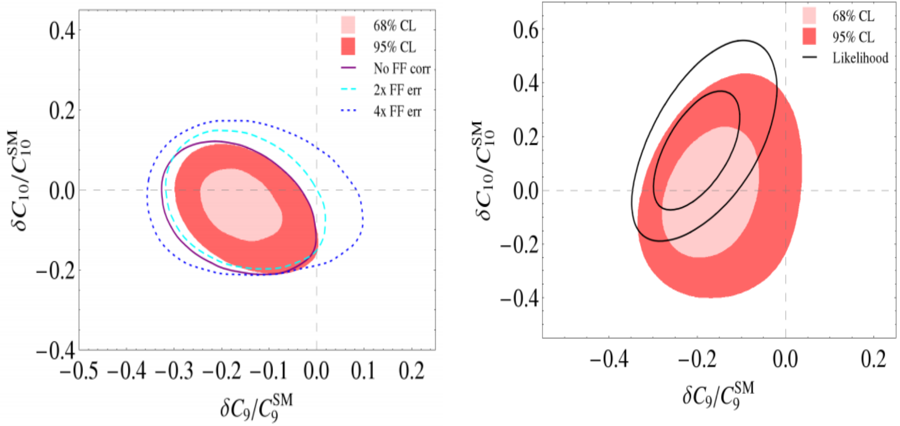
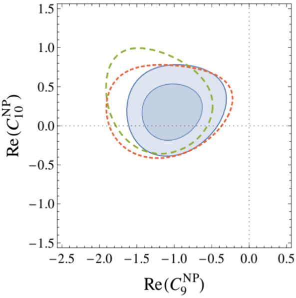
  a fit to LCSRs Barucha, Straub, Zwicky and Lattice Bouchard et al, Horgan et al.
- ▷ Also fits LHCb Method-of-Moments results.



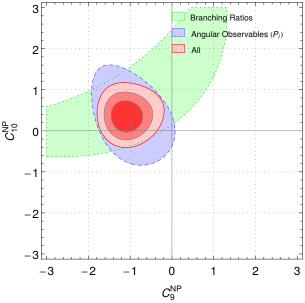
:: Other Fits

Good agreement among the different fits:

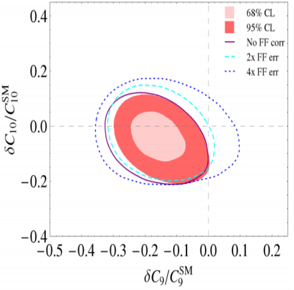
AS



DHMV



HMN



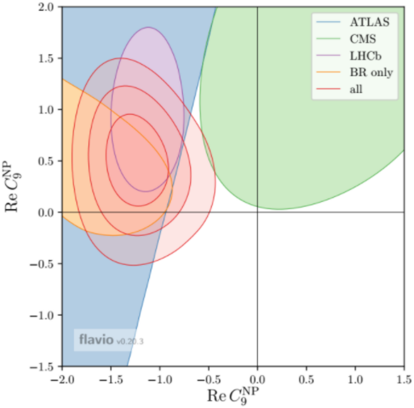
Implies that the differences in the various analyses are not so relevant in the final result.

Of course, each analysis separately has its own checks of hadronic uncertainties, etc.

:: Implications of new CMS + ATLAS ?

Altmannshofer, Straub 2017

fresh off the press $\mathcal{C}_9^{\rm NP} = -1.2$ anomaly persists



SM disfavoured w.r.t.

- scenario w/ indep. $\mathcal{C}_9^{\rm NP}$ and $\mathcal{C}_{10}^{\rm NP}$ by 4.6σ
- scenario w/ indep. $\mathcal{C}_9^{\rm NP}$ and $\mathcal{C}_{9'}^{\rm NP}$ by 4.8σ

new data on angular distribution

- increase the tension (ATLAS)
- decrease the tension (CMS)

"[including ATLAS and CMS data] We find that the significance of the tension remains strong. Assuming the tension to be due to NP, a good fit is obtained with a negative NP contribution to the Wilson coefficient $\mathcal{C}_9$."

:: Summary 1

◦ A NP contribution $\mathcal{C}_{9\mu}^{\rm NP} \sim -1$ gives a **substantially improved fit** 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
- ▷ R_K

All these receive, in general, quite different contributions from hadronic operators.

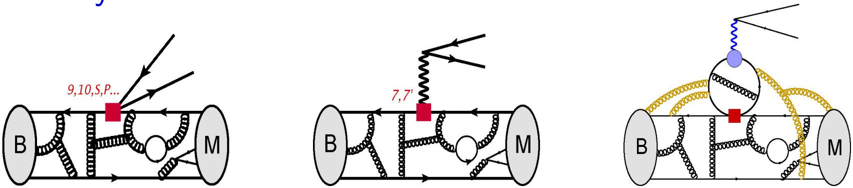
◦ Different fits with similar results:

- Descotes-Genon, Matias, Virto, 1307.5683 [hep-ph]
- Altmannshofer, Straub, 1308.1501 [hep-ph], 1411.3161 [hep-ph]
- Beaujean, Bobeth, van Dyk, 1310.2478 [hep-ph]
- Horgan, Liu, Meinel, Wingate, 1310.3887 [hep-ph]
- Hurth, Mahmoudi, Neshatpour, 1410.4545[hep-ph], 1603.00865 [hep-ph]

◦ ATLAS + CMS results do not change the global picture

2. Hadronic Contributions

:: 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:

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

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

Non-Local:

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

Two theory issues:

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

:: 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

$$\mathcal{H}^\mu(q^2) \equiv i \int \mathrm{d}^4x\, e^{iq\cdot x} \,\langle \bar{K}^*(k,\eta)|\, T\{j^\mu_{\rm em}(x), \mathcal{C}_1\mathcal{O}_1 + \mathcal{C}_2\mathcal{O}_2(0)\}|\bar{B}(p)\rangle$$

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

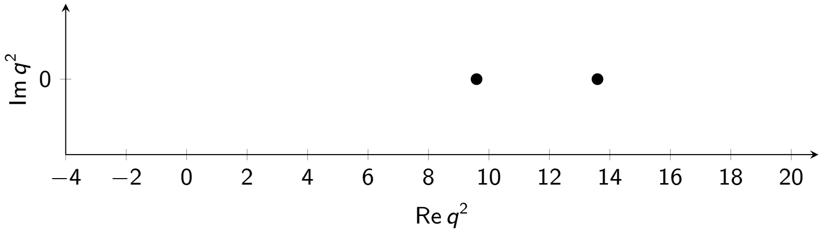
- ▷ $S_\lambda^{\alpha\mu}$ – basis of Lorentz structures (carefully chosen)
- ▷ $\mathcal{H}_\lambda$ – Lorentz invariant correlation functions
- ▷ λ – polarization states ($\perp$, $\parallel$, 0)

The idea :

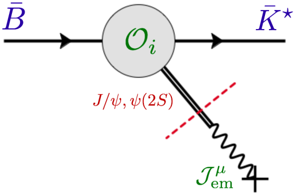
- ▷ Understand analytic structure of $\mathcal{H}_\lambda(q^2)$ to write a general parametrisation consistent with QCD.
- ▷ Use **suitable** experimental information to constrain the correlator.
- ▷ Use theory to constrain the correlator in **suitable** kinematic points.

:: Hadronic correlator : Analytic structure

Bobeth, Chrzaszcz, van Dyk, Virto

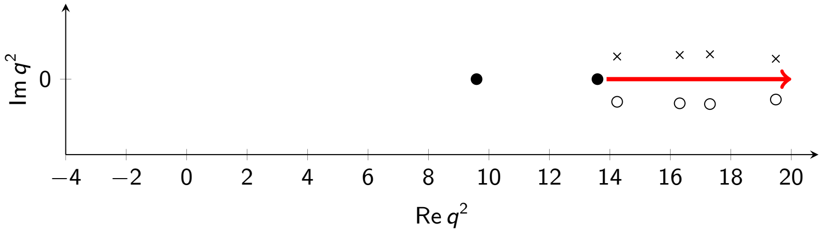


- narrow charmonia, assumed to be stable

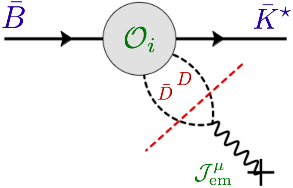


:: Hadronic correlator : Analytic structure

Bobeth, Chrzaszcz, van Dyk, Virto

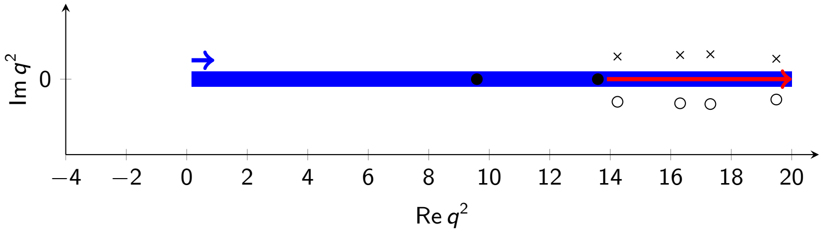


- ● narrow charmonia, assumed to be stable
- red branch cut from $D\bar{D}$ production
- ○ broad charmonia, decaying to $D\bar{D}$
- × potential mirror poles

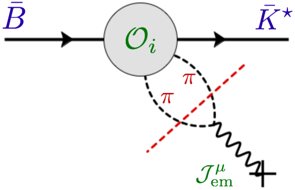


:: Hadronic correlator : Analytic structure

Bobeth, Chrzaszcz, van Dyk, Virto

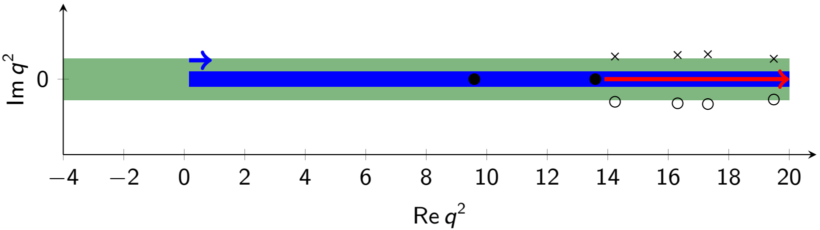


- ● narrow charmonia, assumed to be stable
- red branch cut from $D\bar{D}$ production
- ○ broad charmonia, decaying to $D\bar{D}$
- × potential mirror poles
- blue branch cut from light hadrons

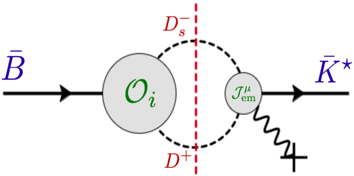


:: Hadronic correlator : Analytic structure

Bobeth, Chrzaszcz, van Dyk, Virto



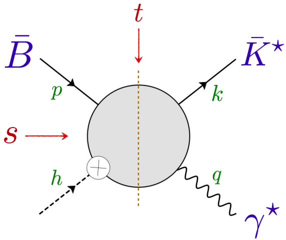
- ● narrow charmonia, assumed to be stable
- red branch cut from $D\bar{D}$ production
- ○ broad charmonia, decaying to $D\bar{D}$
- × potential mirror poles
- blue branch cut from light hadrons
- green q^2-dep. imaginary due to branch cut in p^2

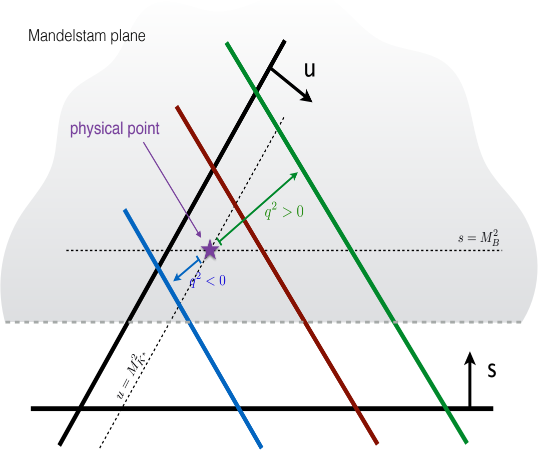


:: Understanding the p^2 cut

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 $q^2 > 0$

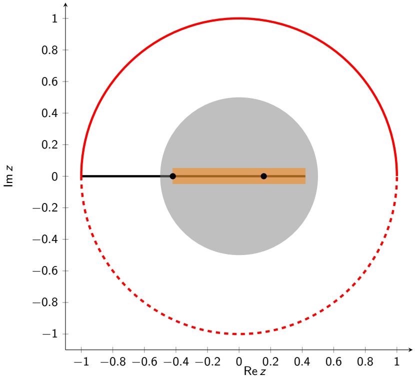
:: Parametrization A : $J/\psi, \psi(2s)$ poles + $D\bar{D}$ cut

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

$$\mathcal{H}_\lambda(q^2) = \frac{1}{q^2 - M^2_{J/\psi}} \frac{1}{q^2 - M^2_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(q^2)$$



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 $-5\,\text{GeV}^2 \leq q^2 \leq 14\text{GeV}^2$

:: 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:

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

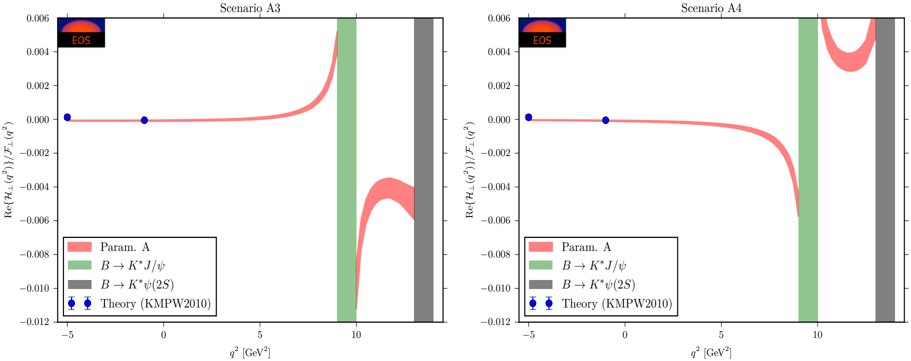
- first term is usual form-factor-like contribution
- second term arises from soft-gluon effects only
- third term arises from NLO corrections (produces p^2 cut !!)

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

:: Results Parametrization A Preliminary

Bobeth, Chrzaszcz, van Dyk, Virto

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



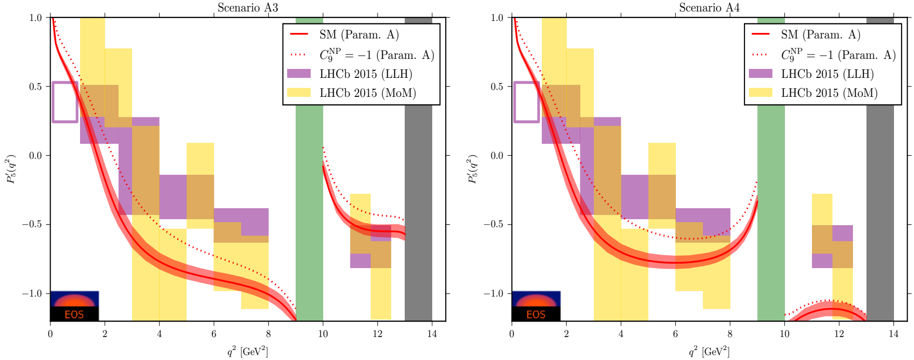
Discrete ambiguity in phases of the residues : (only two shown)

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'



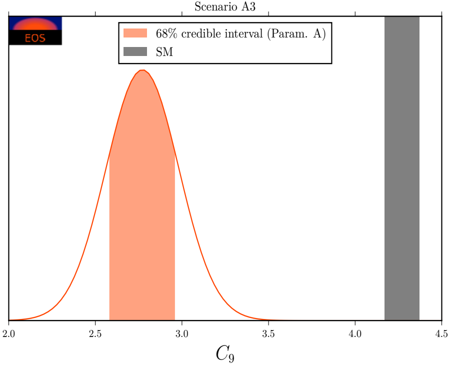
Left : $\phi_{J/\psi} = \pi$, $\phi_{\psi(2S)} = 0$ **Right :** $\phi_{J/\psi} = \phi_{\psi(2S)} = \pi$

▷ 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 2

- 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
  - Complex parametrization A : needs analytic NLO Greub, Virto w.i.p.
  - Parametrization B : includes light-hadron cut from ψ decay

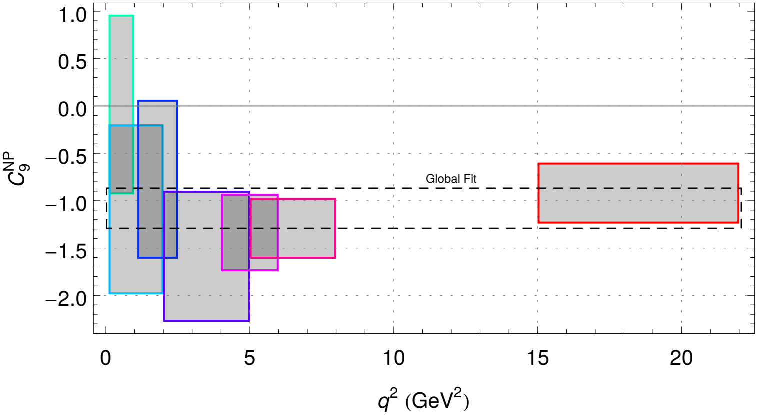
Keep an eye on this !!

Back-up

:: Hadronic correlator: are we missing something?

Descotes-Genon, Hofer, Matias, Virto

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

:: Outlook: Potential of inclusive measurements at Belle-2

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