University of Zurich[UZH]

Systematic approach to non-local charm contributions in exclusive $b \to s\ell\ell$ decays

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based on Bobeth/Chrzaszcz/DvD/Virto 1705.XXXXX

SM@LHC in Amsterdam

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Effective theory for $b \to s$ transitions

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

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

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

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

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

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

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]

$$\mathcal{C}_{7\rm eff}^{\rm SM} = -0.3,\ \mathcal{C}_{9\ell}^{\rm SM} = 4.1,\ \mathcal{C}_{10\ell}^{\rm SM} = -4.3,\ \mathcal{C}_1^{\rm SM} = -0.4,\ \mathcal{C}_2^{\rm SM} = 1.1,\ \mathcal{C}_{\rm rest}^{\rm SM} \lesssim 10^{-2}$$

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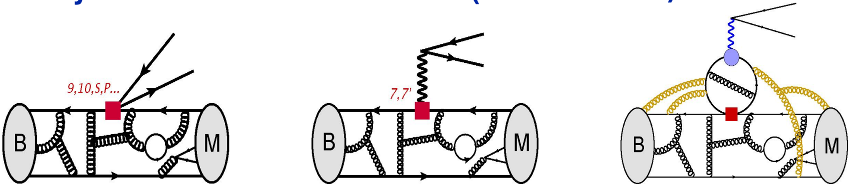
numerically leading operators

source of largest systematic uncertainty

$$\mathcal{C}_{7\text{eff}}^{\text{SM}} = -0.3,\ \mathcal{C}_{9\ell}^{\text{SM}} = 4.1,\ \mathcal{C}_{10\ell}^{\text{SM}} = -4.3,\ \mathcal{C}_1^{\text{SM}} = -0.4,\ \mathcal{C}_2^{\text{SM}} = 1.1,\ \mathcal{C}_{\text{rest}}^{\text{SM}} \lesssim 10^{-2}$$

Theory of exclusive $B \to M\ell^+\ell^-$ (in a nutshell)



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

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:

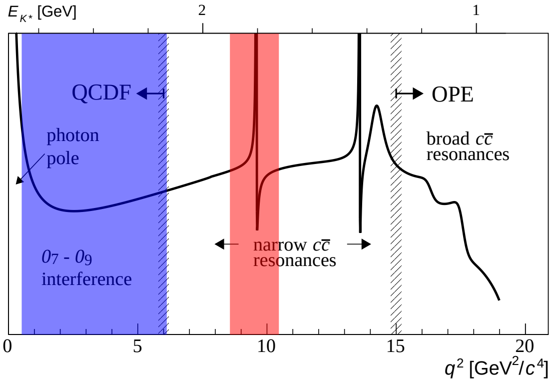
$$\mathcal{H}_\lambda^\mu = -\frac{16 i\pi^2}{q^2} \sum_{i=1..6,8} \mathcal{C}_i \int \mathrm{d}^4x\, e^{iq\cdot x} \langle M_\lambda | T\left\{ \mathcal{J}_{\text{em}}^\mu(x), \mathcal{O}_i(0) \right\} | B\rangle$$

Two theory issues:

1. **form factors** (LCSRs, LQCD, symmetry relations . . .)
2. **nonlocal hadronic contribution** (SCET/QCDF, OPE, LCOPE . . .)

The decay $B \to K^* \mu^+ \mu^-$

[sketch taken from Blake/Gershon/Hiller 1501.03309]

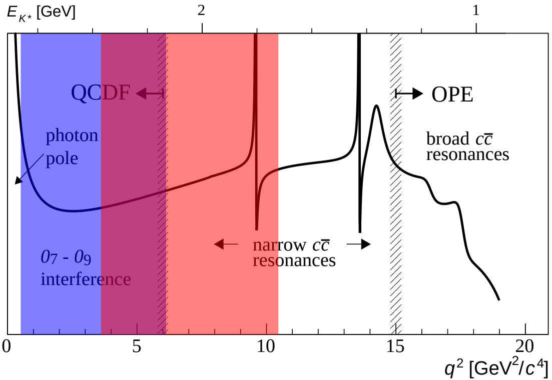


region of interest (for this talk)

polluted by $B \to K^* J/\psi$ “background”

The decay $B \to K^* \mu^+ \mu^-$

[sketch taken from Blake/Gershon/Hiller 1501.03309]



region of interest (for this talk)

polluted by $B \to K^* J/\psi$ "background"

- uncertainty w.r.t. onset of $B \to K^* J/\psi$ pollution poses largest systematic theory uncertainty

Hadronic correlator : Decomposition

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

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

here

$S_\lambda^{\alpha\mu}$ basis of Lorentz structures (carefully chosen)

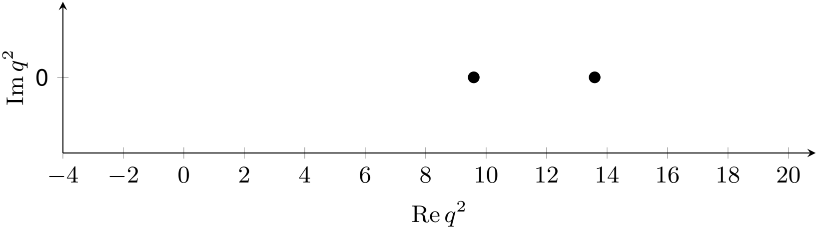
$\mathcal{H}_\lambda$ Lorentz invariant correlation functions

λ polarization states $(\perp, \parallel, 0)$

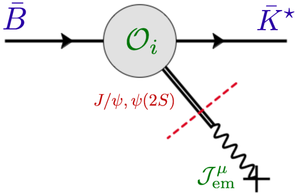
our idea:

– understand analytic structure of the $\mathcal{H}_\lambda(q^2)$ to write a general parametrisation consistent with QCD.

Hadronic correlator : Analytic structure



- narrow charmonia, assumed to be stable



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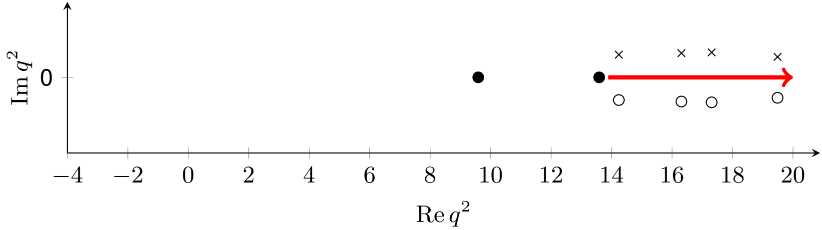
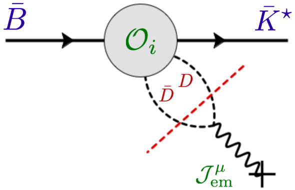


- ● narrow charmonia, assumed to be stable
- red branch cut from $D\overline{D}$ production
- ○ broad charmonia, decaying to $D\overline{D}$
- × potential mirror poles



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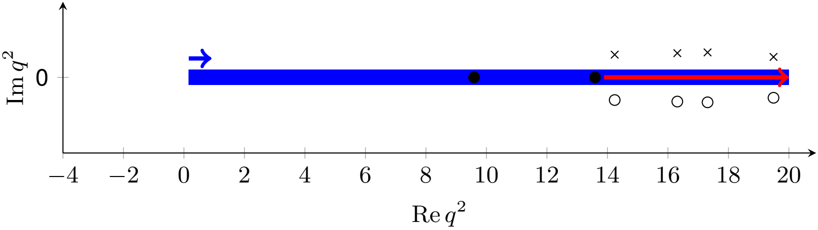

- ● narrow charmonia, assumed to be stable
- red branch cut from $D\overline{D}$ production
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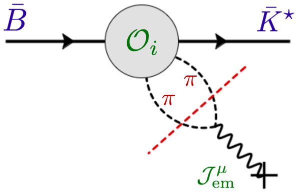
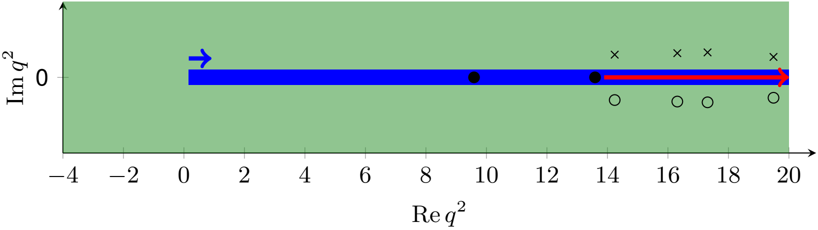
- × potential mirror poles
- blue branch cut from light hadrons



Hadronic correlator : Analytic structure



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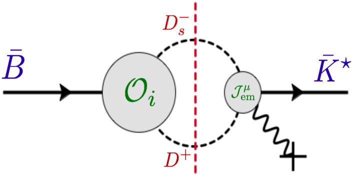
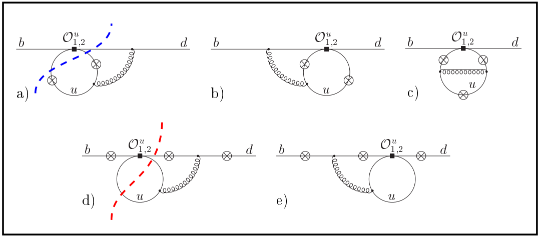
- green q^2-dep. imaginary part (due to branch cut in p^2)



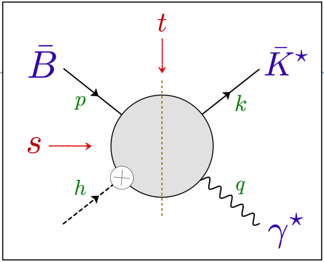
Understanding the p^2 cut

- p^2 cut arises from loop contributions
  - at one loop: only right-hand cut in q^2
  - at two loop: no analytic results available for $b \to s c \bar{c}$
    series expansion available [see e.g. Greub/Pilipp/Schupbach 2008]
- turn to $b \to d u \bar{u}$ instead as a toy analysis, for which analytic two-loop results are available [Seidel 2004]



- at two loop: two sources of p^2 cut
  - $u\bar{u}d$ on shell at $q^2 < 0$
  - $d\bar{d}d$ on shell at $q^2 < 0$

Understanding the p^2 cut



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

– consider Mandelstam variables

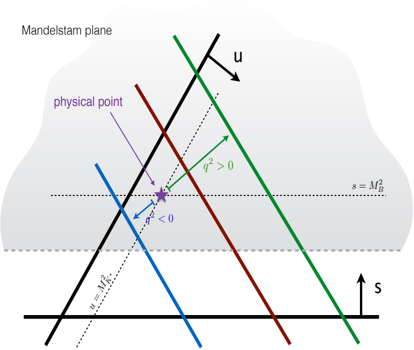
$$s \equiv (p+h)^2 \quad \longrightarrow \quad M_B^2$$

$$u \equiv (k-h)^2 \quad \longrightarrow \quad M_{K^*}^2$$

$$t \equiv (q-h)^2 \quad \underset{\text{physical point}}{\longrightarrow} \quad q^2$$

– s independent of t

– cut in $s \sim p^2$ does not translate into cut in $t \sim q^2$



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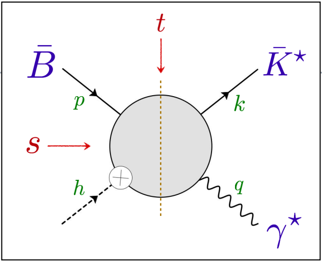

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– s independent of t

  – cut in $s \sim p^2$ does not translate into cut in $t \sim q^2$

– two correlators:

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

– both are analytic at $q^2 \leq 0$

– both have branch cuts at $q^2 > 0$

– the same dispersion relation governs their q^2-dependence

Setup

task 1 parametrize the correlator $\mathcal{H}_\mu$

- take care to preserve the analytic structure

task 2 fit the parametrization to *suitable* inputs

a theoretical inputs far away from the onset of the J/ψ pole
b experimental input on the J/ψ and $\psi(2S)$ pole

task 3 predict observables in $B \to K^* \mu^+ \mu^-$ decays

a assume the Standard Model holds
b assume a benchmark point $\mathcal{C}_9^{\text{NP}} = -1$, compatible with present global fits

task 4 fit the parametrization also to $B \to K^* \mu^+ \mu^-$ data

a test if the predictions fit the data
b test whether modifications to $\mathcal{C}_9^{\text{NP}}$ improve the fit

Parametrization A : $J/\psi, \psi(2s)$ poles + $D\overline{D}$ cut (task 1 ✓)

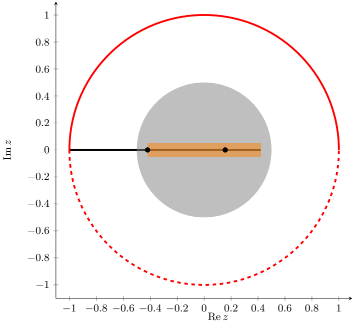
Motivated by famous "z-parametrization" of form factors

[Boyd/Grinstein/Lebed hep-ph/9412324]

1. extract the poles

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

2. $\hat{\mathcal{H}}_\lambda(q^2)$ is analytic except for $D\overline{D}$ cut.
3. Perform conformal mapping $q^2 \mapsto z(q^2)$
4. $\hat{\mathcal{H}}_\lambda(z)$ analytic within unit circle $|z| = 1$
5. Taylor expand $\hat{\mathcal{H}}_\lambda(z)$ around $z = 0$
6. Good convergence expected since $|z| < 0.48$ for $-5\,\text{GeV}^2 \leq q^2 \leq 14\text{GeV}^2$



Theory inputs (task 2a ✓)

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

[Khodjamirian et al. 1006.4945]

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

$$\mathcal{H}_\perp(q^2) = \left[\# \times g(q^2, m_c^2) \; + \; \frac{\alpha_s}{4\pi} \times \# \times \{F_1^9, \dots\}\right] \times \mathcal{F}_\perp(q^2)$$
$$+ \; \# \times \widetilde{\mathcal{V}}_1(q^2)$$
$$+ \; \# \times \phi_B \otimes \mathcal{T}_\perp \otimes \phi_{K^*}$$

- first line contains form-factor-like contributions
  - LO contribution
  - NLO correction (produces p^2 cut !!) [Asatryan et al. hep-ph/0109140]
- third term arises from soft-gluon effects only [Khodjamirian et al. 1006.4945]
- fourth term arises from hard-gluon effects only (w/ spectator)

[Beneke et al. hep-ph/0106067 and hep-ph/0412400]

details:

- compute $\mathcal{H}_\lambda / \mathcal{F}_\lambda$ at $q^2 = -1\,\text{GeV}^2$ and $q^2 = -5\,\text{GeV}^2$
- include (substantial) correlations across correlators and across q^2

Experimental inputs (task 2b ✓)

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

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

details:

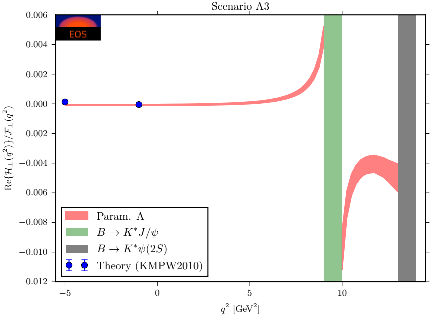
- residues of the correlator can be expressed in terms of $B \to K^*\psi$ amplitudes
- $\mathcal{B}$ and 4 angular observables measured in $B \to K^* J/\psi$ and $B \to K^*\psi(2S)$

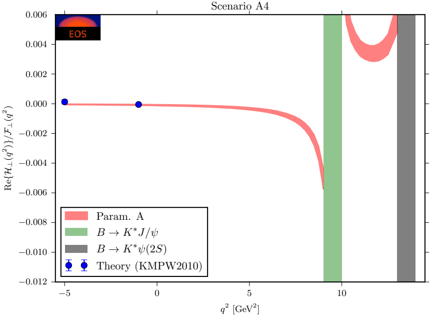
[BaBar 2007, Belle 2014, LHCb 2013]

- allows to constrain all moduli and two relative phases of the amplitudes, and therefore of the residues of the correlator.

Preliminary! Predictions for the correlator

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





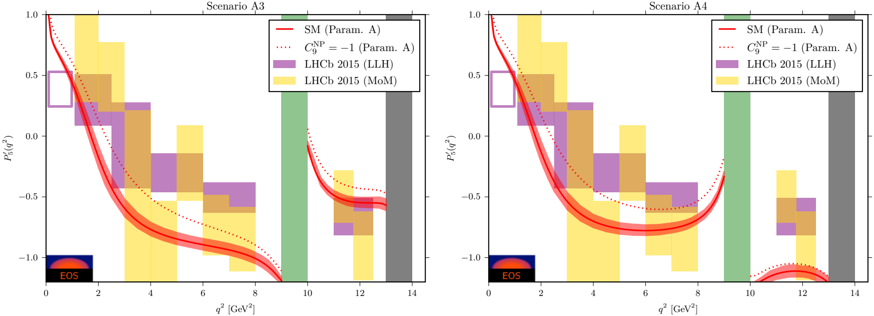
discrete ambiguity in phases of the residues: (only two shown)

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

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

Preliminary! Predictions for P_5' (tasks 3a,3b ✓)

prediction within Standard Model (SM) and one benchmark point ($\mathcal{C}_9^{\text{NP}} = -1$)

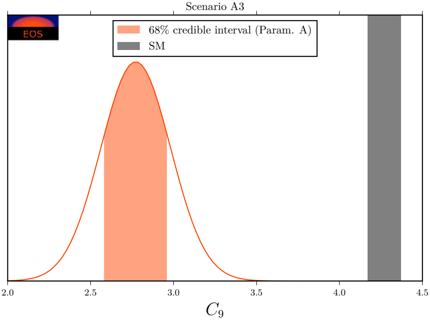


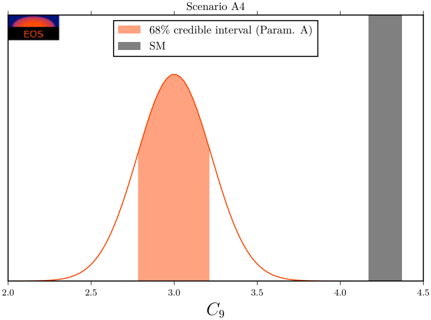
Left : $\phi_{J/\psi} = \pi\ ,\ \phi_{\psi(2S)} = 0$ **Right :** $\phi_{J/\psi} = \phi_{\psi(2S)} = \pi$

- **great potential:** for the first-time, fits gain sensitivity to inter-resonance bin
  - more comprehensive usage of available data
  - complementary information compared to below-resonance data

Preliminary! Challenge $B \to K^* \mu^+ \mu^-$ data (task 4b ✓)

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





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

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

– for all choice of phases: pull $> 4\sigma$

Summary and outlook

- framework to access nonlocal correlator
  - first approach to use both theory inputs and experimental constraints in a 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 shown here [Bobeth/Chrzaszcz/DvD/Virto 1705.xxxxx]
  - *complex* parametrization A: needs NLO terms [analytic $\to$ Greub/Virto w.i.p.]
  - parametrization B: includes light-hadron cut from ψ decay

Wish list for our experimental colleagues

- rate and full set of angular observables of $B \to K^* \psi(\to \mu^+ \mu^-)$ for both narrow charmonium resonances
  - $\psi(2S)$ not available from LHCb!
  - provide results *including* the Z_c states
    removal of Z_c states in recent analyses (e.g. by Belle) complicates our analysis
- smaller charmonium veto windows
- three or more bins between J/ψ and $\psi(2S)$ for rate and angular observables
  - partial overlap with previous veto windows encouraged!