LHCb measurements of rare electroweak decays of b-hadrons

FPCP 2024

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on behalf of the LHCb Collaboration

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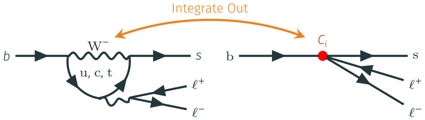
Studying $b \to s\ell^+\ell^-$ transitions

$b \to s\ell^+\ell^-$

- → Flavour Changing Neutral Current (FCNC) process
- → small SM contribution (10^{-9} to 10^{-6})
- → sensitive probe for new physics

Effective Field Theory approach



$$\mathcal{H}_{SM} \longrightarrow \mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i^{SM} + C_i^{NP}) \mathcal{O}_i$$
+ chiral flipped

Wilson Coefficients: C_i

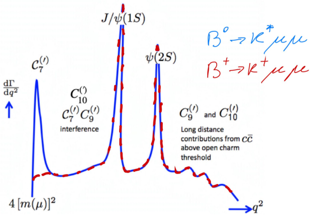
- → Perturbative, short distance physics
- → Integrates heavy physics, sensitive to NP effects

Operators: $\mathcal{O}_i$

- → Non-perturbative, long distance physics
- → Strong interactions, difficult to calculate

Operator $\mathcal{O}_i$	$B_{s(d)} \to V_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to V_{s(d)}\gamma$
$\mathcal{O}_7$ EM	✓		✓
$\mathcal{O}_9$ Vector dilepton	✓		
$\mathcal{O}_{10}$ Axial-vector dilepton	✓	✓	
$\mathcal{O}_{S,P}$ (Pseudo-)Scalar dilepton	(✓)	✓	

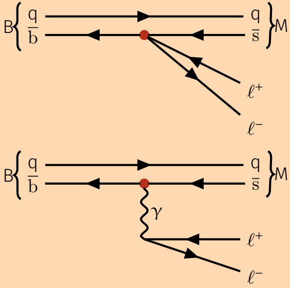
$$q^2 \equiv m^2_{\mu\mu}$$



*Courtesy Nicola Serra

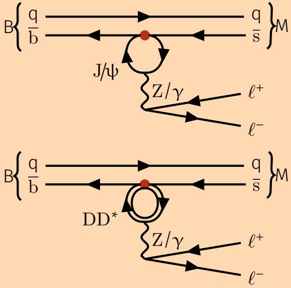
Local and Non-local Effects

Local contributions ($\mathcal{O}_{9,10,7}$)

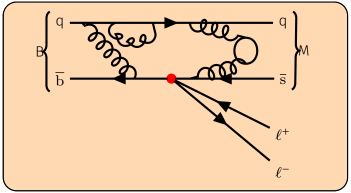


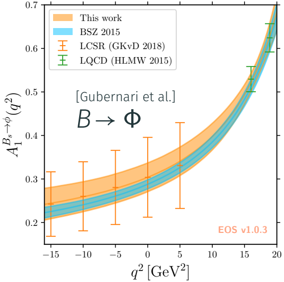
Non-local contributions ($\mathcal{O}_{1q,2q}$)

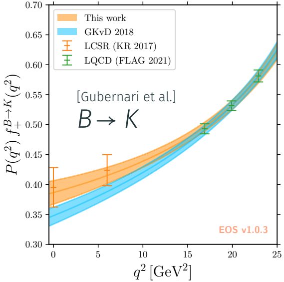
Intermediate states



Local Hadronic effects

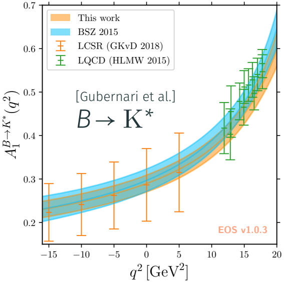






The form factors are difficult to calculate and leading source of theoretical uncertainty.
Two complimentary approaches,

- Lattice QCD in high q^2 region (low hadronic recoil) [HPQCD], [FNAL/MILC]
- Light Cone Sum Rules in low or -ve q^2 region [Gubernari et al.], [Khodjamirian and Rusov], [Bharucha, Bharucha and Zwicky], [Khodjamirian et al.]

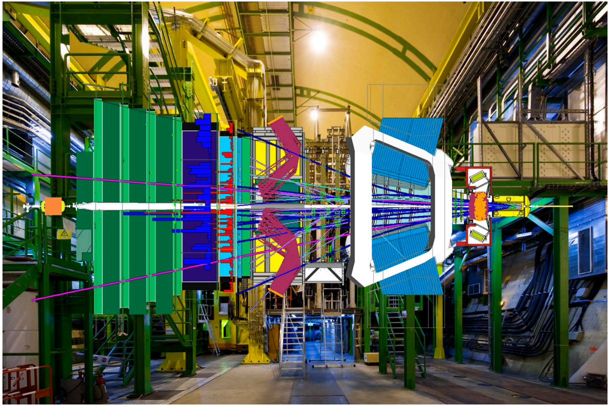


Interpolate to full q^2

LHCb Detector

Forward arm spectrometer ($2 < \eta < 5$) to study b and c hadron decays.

Excellent particle ID
μ ID: 97%, K ID: 95%,
($\pi \to \mu$ misID: 1-3%),
($\pi \to K$ misID: ~ 5%)

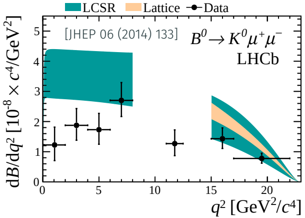


Excellent vertex and impact parameter resolution
(σ(IP)=15 +29/p_T[GeV]) μm)

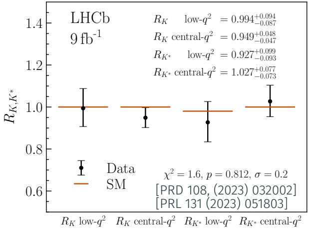
Very efficient triggers:
~ 90% for dimuon channels

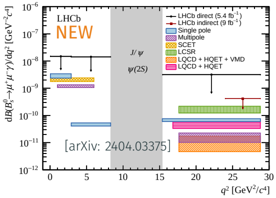
Excellent momentum resolution
$\frac{\Delta p}{p}$ = 0.5% at low p
to 1.0% at 200 GeV/c)

Current Experimental status



$\mathcal{B}\,(b \to s\mu^+\mu^-)$:
Data consistently below SM predictions





$\mathcal{B}\,(B^0_{(s)} \to \mu^+\mu^-)$:
Consistent with SM
$B^0_s \to \mu^+\mu^-\gamma$:
Latest direct limits

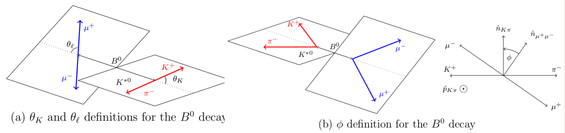
$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\mathrm{SM}}{\cong} 1,$$

Exp. consistent with SM
LFU NP?

(Note: Resonance regions typically removed)

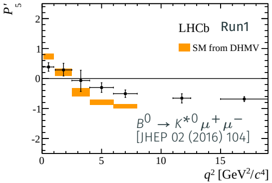
Angular analyses

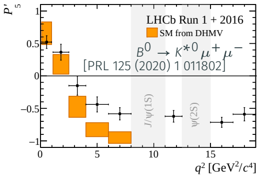
Decay described by q^2 and three angles $\hat{\Omega} = (\theta_l, \theta_k \text{ and } \phi)$



$$\frac{d^4\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{d\hat{\Omega}dq^2} = \sum_i J_i(q^2) f_i(\hat{\Omega})$$

Angular coefficients angular functions



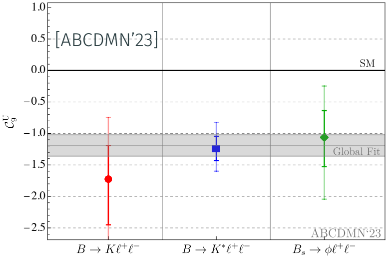


- Global fit to CP averaged observables show deviation with SM change from **3.0σ** to **3.3σ** between **3 fb^{-1}** and **4.6 fb^{-1}**
- Large dependence on treatment of SM hadronic effects
- Tensions also seen in $B^+ \to K^{*+}\mu^+\mu^-$ and $B_s^0 \to \Phi\mu^+\mu^-$ decays

- $J_i(q^2) \propto (\mathcal{A}_\lambda \mathcal{A}_\lambda^*)$, C_i and FF dependent amplitudes.
- Coefficients $P_{1,\ldots,8}$ constructed to cancel form factors to leading order
- Additional nuisance terms introduced for non-resonant S-wave configuration.

(Note: Resonance regions typically removed)

Global fit



Fit to C_9^U [NP] assuming no NP in other Wilson Coefficients

Potential explanations:

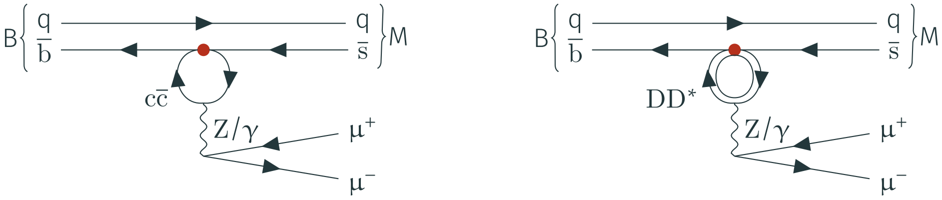
- Could it be lepton universal new physics?
- Could it be new physics in third generation leptons feeding down to lower generations? (possibly linking anomalies in $\mathrm{b} \to \mathrm{c}\ell\overline{\nu}_\ell$ and $\mathrm{b} \to \mathrm{s}\ell^+\ell^-$)

OR

- Could it be underestimated non-local ”charm-loop” effects?

Non-local charm-loop effects

Experimentally can mimic NP and difficult to estimate theoretically



Can we measure these non-local effects from data?

A closer look using $B^0 \to K^{*0}\mu^+\mu^-$ decays

Method 1
z Expansion

- Fit to q^2 regions using a polynomial to describe the non-local effects.
- Use theoretical and experimental inputs to constrain them.

Method 2
Dispersion

- Unbinned fit to the full q^2 spectrum.
- Use dispersion relations to explicitly model non-local states

z-Expansion Amplitude Form

[PRD 109 (2024) 052009]
[PRL 132 (2024) 131801]

$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ \left[(C_9 \pm C_9') \mp (C_{10} \pm C_{10}') \right] \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[(C_7 \pm C_7') \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

Wilson Coefficients, C_i

- Real part of C_9, C_9', C_{10} and C_{10}' treated as free fit parameters. Imag. fixed to zero

Local Form Factors, $\mathcal{F}_\lambda(q^2)$

- Constrained to LCSR + Lattice inputs
  [Gubernari, Kokulu & van Dyk] + [Horgan, Liu, Meinel & Wingate]

Non-local hadronic matrix elements (charm-loop), $\mathcal{H}_\lambda(q^2)$

- Exploit analytic properties of hadronic matrix elements,
- Following [Gubernari, Reboud, van Dyk & Virto],

$$q^2 \to z(q^2) \equiv \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

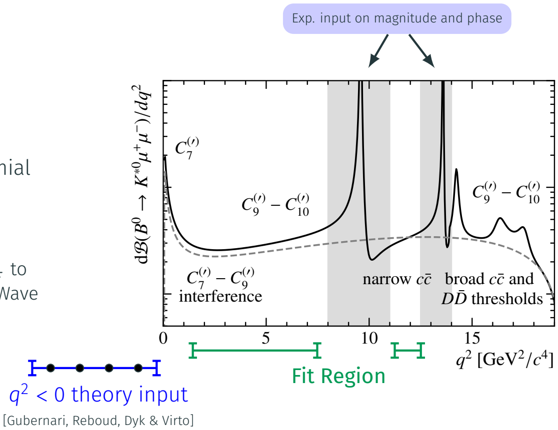
$$\mathcal{H}_\lambda(z) = \frac{1 - z z_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z_{\psi(2S)}}{z - z_{\psi(2S)}} \phi_\lambda^{-1}(z) \sum_k a_{\lambda,k} z^k,$$

Polarisation
$\lambda \in (||, \perp, 0)$

- Experimental inputs for magnitudes and phases of resonances [PRD 90 (2014) 112009], [PRD 76 (2007) 031102], [PRD 88 (2013) 074026], [PRD 88 (2016) 052002], [EPJC 72 (2012) 2118]

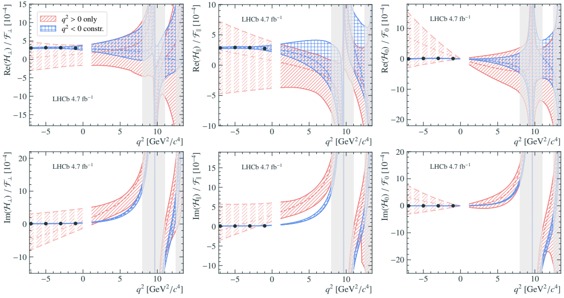
z-Expansion Fit Strategy

- Using 4.7 fb^{-1} of LHCb data (Run1+2016)
- Unbinned fit for FFs, WCs, and non-local polynomial coefficients $a_{\lambda,k}$
- 6D fit to 3 angles, q^2, $m^2(K\pi)$ and $m(K\pi\mu\mu)$
  - → Amplitudes modified to incl. dependence on $m_{K\pi}$ to model P-Wave as relativistic Breit-Wigner and S-Wave with LASS
  - → $m(K\pi\mu\mu)$ modelled with double Crystal Ball
- BF measured relative to $B^0 \to K^+\pi^- J/\psi$



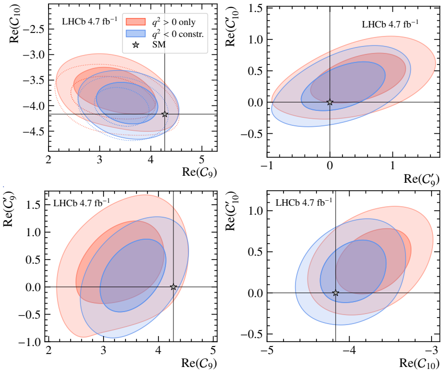
Two versions of fit: Without and with theory input on non-local component from $q^2 < 0$

[PRD 109 (2024) 052009]
[PRL 132 (2024) 131801]



Good agreement seen between both versions, without and with $q^2 < 0$ theory input

Deviation from SM	ΔC_9	ΔC_{10}	$\Delta C_9'$	$\Delta C_{10}'$
$q^2 > 0$ only	1.9σ	1.5σ	0.9σ	1.5σ
$q^2 < 0$ prior	1.8σ	0.9σ	0.5σ	1.0σ



Dispersion Amplitude Form

NEW [arXiv:2405.17347]

[Cornella,Isidori,König,Liechti,Owen,Serra]

Non-local effects described as corrections to C_9.

$$C_9 \rightarrow C_9^{\mathrm{eff},\lambda} = C_9 + Y_{\mathrm{c\bar{c}}}^{(0),\lambda} + \Delta Y_{light}^{1P,\lambda}(q^2) + \Delta Y_{\mathrm{c\bar{c}}}^{1P,\lambda}(q^2) + \Delta Y_{\mathrm{c\bar{c}}}^{2P,\lambda}(q^2) + Y_{\tau\tau}(q^2)$$

$$C_7^{\mathrm{eff},\lambda} = C_7 + \epsilon^{\lambda} e^{i\omega^0}$$

Dispersion Amplitude Form

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$$C_7^{\mathrm{eff},\lambda} = C_7 + \epsilon^{\lambda} e^{i\omega^0}$$

Local Contributions

Wilson Coefficients

Real part of C_9, $C_9^{'}$, C_{10} and $C_{10}^{'}$ treated as free fit parameters.
Imaginary part set to 0, implicitly assumes no CPV in $B \rightarrow K^* \mu^+ \mu^-$ decays

Polarisation dependent shift

Included as a fit parameter to allow for helicity dependent complex phase

Non-local effects described as corrections to C_9.

[Cornella,Isidori,König,Liechti,Owen,Serra]

$$C_9 \to C_9^{\mathrm{eff},\lambda} = C_9 + Y_{c\bar{c}}^{(0),\lambda} + \Delta Y_{light}^{1P,\lambda}(q^2) + \Delta Y_{c\bar{c}}^{1P,\lambda}(q^2) + \Delta Y_{c\bar{c}}^{2P,\lambda}(q^2) + Y_{\tau\tau}(q^2)$$

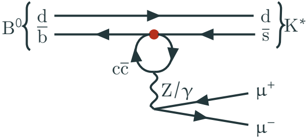
$$C_7^{\mathrm{eff},\lambda} = C_7 + \epsilon^{\lambda} e^{i\omega^0}$$

Non-Local Contributions

Subtraction term

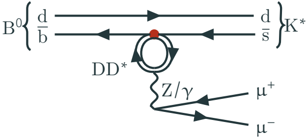
Theoretically calculated at negative q^2
[JHEP 04 (2020) 012]
Introduced to ensure convergence of dispersion relation.
Negligible impact for light resonances

1-particle contributions



Includes vector resonances:
light → $\rho(770)$, $\omega(782)$, $\phi(1020)$,
$c\bar{c}$ → J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$
Mag (except J/ψ) and phase are fit parameters

2-particle contributions



Includes non-resonant:
DD, DD^*, D^*D^*
Real and Imag. parts are fit parameters

NEW [arXiv:2405.17347]

[Cornella,Isidori,König,Liechti,Owen,Serra]

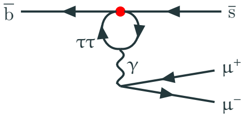
Non-local effects described as corrections to C_9.

$$C_9 \to C_9^{\mathrm{eff},\lambda} = C_9 + Y_{c\bar{c}}^{(0),\lambda} + \Delta Y_{light}^{1P,\lambda}(q^2) + \Delta Y_{c\bar{c}}^{1P,\lambda}(q^2) + \Delta Y_{c\bar{c}}^{2P,\lambda}(q^2) + Y_{\tau\tau}(q^2)$$

$$C_7^{\mathrm{eff},\lambda} = C_7 + \epsilon^{\lambda} e^{i\omega^0}$$

Non-Local Contributions

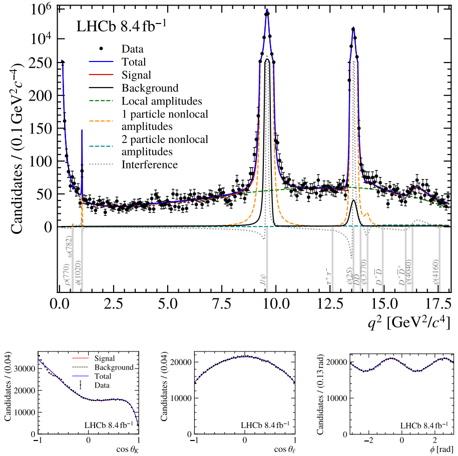
Tau-scattering contribution



Wilson C_9^{τ} is fit paramter
gives indirect access to BF($B^0 \to K^* \tau^+ \tau^-$)

NEW [arXiv:2405.17347]

Unbinned fit to full q^2 using 8.4 fb^{-1} (2011+2012, 2016+2017+2018) LHCb data



- Total 150 fit parameters
- From simulation:
  - → Acceptance model
- From data:
  - → Resolution
  - → S-Wave Parameters
  - → Background model
  - → Non-local states
- From theory
  - → Local $B \to K^*$ form factors gaussian constrained [Gubernari, Reboud, van Dyk & Virto]
  - → Subtraction point for $c\bar{c}$ [Asatrian, Greub & Virto]

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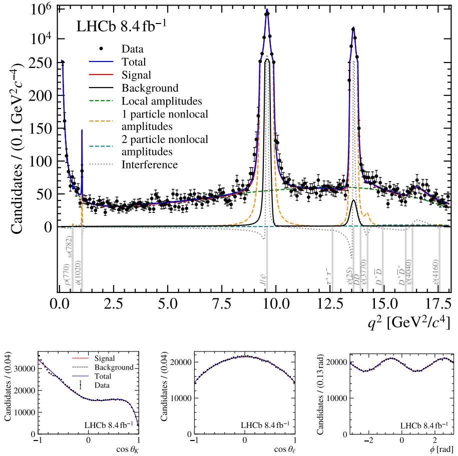
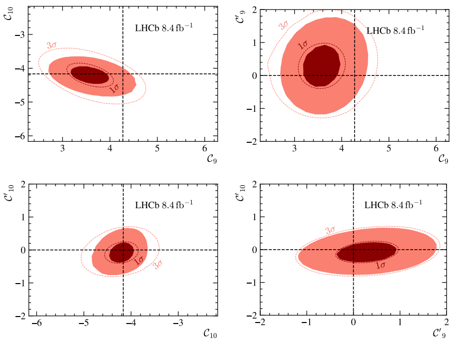


	ΔC_9	ΔC_{10}	$\Delta C_9'$	$\Delta C_{10}'$	C_9^τ
Deviation from SM	2.1σ	0.6σ	0.7σ	0.4σ	0.4σ

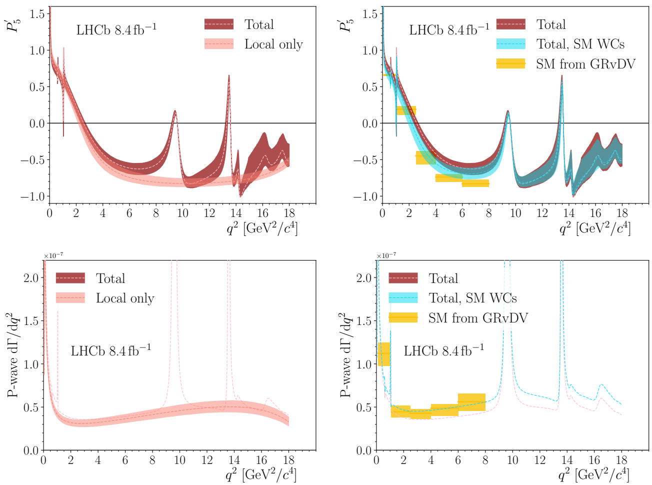
$|C_9^\tau| < 500$ at 90% C.L., $C_9^{\tau,SM} \sim 4$

Current best limits $|C_9^\tau| < 680$ (600) at 90% C.L. $C_{10}^\tau = SM$ ($C_{10}^\tau = -C_9^\tau$)
[PRD 108, L011102 (2023)], flavio



Dispersion, Impact of non-local

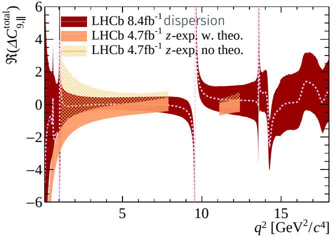
NEW [arXiv:2405.17347]

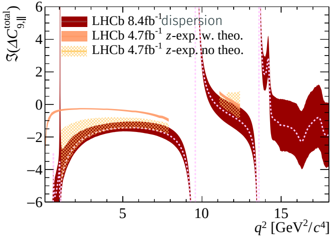


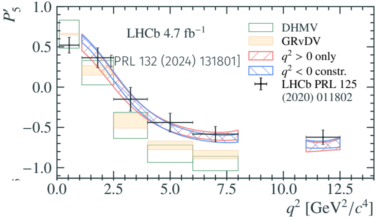
- Modification of differential observable from non-local state
- Cyan band on right calculated by fixing WC to SM values and non-local from data.
- Data seem to prefer non-local values larger than SM prediction
- Nevertheless, Wilson C_9 still prefers a shifted value w.r.t SM (indicated by the Total band)

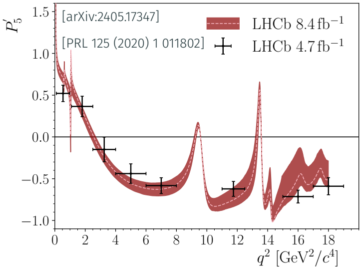
Compatibility of $B^0 \to K^{*0}\mu^+\mu^-$ Analyses

- Polarisation dependent amplitude of non-local states (eg. ||)
- Good agreement seen between the two analyses.









- Comparison of P_5' with binned analysis (black points)
- Good agreement between the different analyses

Data consistently prefers a deviation from SM

Conclusion

- Imperative to understand charm-loop effects to properly quantify NP in $\mathrm{b} \to \mathrm{s}\ell^+\ell^-$
- Explored two analyses with varying level of model dependence
- Data prefers NP in C_9 at 1.8-2.1σ level (to a lesser significance in other variables)

Coming up next in the near future,

- Updated binned measurement of $B^0 \to K^{*0}\mu^+\mu^-$ using full Run1+Run2 LHCb data
- Updated unbinned measurement of $B^0 \to K^{*0}\mu^+\mu^-$ with the z-expansion method using full Run1+Run2 LHCb data
- A minimally model dependent ansatz analysis to extract q^2 amplitudes of $B^0 \to K^{*0}\mu^+\mu^-$ using full Run1+Run2 LHCb data [Egede, Patel & Petridis]
- Unbinned measurement of fit to full q^2 of $\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-$ decay using full Run1+Run2 LHCb data
- Various analysis ongoing for direct measurement of $\mathrm{b} \to \mathrm{s}\tau^+\tau^-$ (or set competitive limits)

Thanks for listening!

Questions?

Backup

Wilson Coefficient values from $B^0 \to (K^{*0} \to K^+\pi^-)\mu^+\mu^-$

Analysis	C_9	C_{10}	C_9'	C_{10}'	C_9^τ
z-expansion $q^2 > 0$ only	$3.34^{+0.53}_{-0.57}$	$-3.69^{+0.29}_{-0.31}$	$0.48^{+0.49}_{-0.55}$	$0.38^{+0.28}_{-0.25}$	–
z-expansion $q^2 < 0$ constr.	$3.59^{+0.33}_{-0.46}$	$-3.93^{+0.27}_{-0.28}$	$0.26^{+0.40}_{-0.48}$	$0.27^{+0.25}_{-0.27}$	–
Dispersion	3.56±0.33	-4.02±0.24	0.28±0.43	-0.09±0.22	-100±279

Angular analysis of $B^0 \to (K^{*0} \to K^+\pi^-)\mu^+\mu^-$

- The angular coefficients F_L, A_{FB} and S_i depend on Wilson coefficients and form factors
- Combine angular coefficients such that form factors cancel to leading order giving the $P_{1,..,8}$ series coefficients. [Matias et al.]

Famous example:

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

- Need to account for the $K^+\pi^-$ in the non-resonant S-wave configuration.
- Introduce additional angular terms as nuisance parameters.

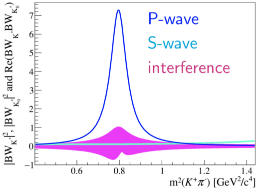
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{S+P}} = (1-F_\mathrm{S})\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}}$$

$$+ \frac{3}{16\pi}F_\mathrm{S}\sin^2\theta_l$$

$$+ \frac{9}{32\pi}(S_{11} + S_{13}\cos 2\theta_l)\cos\theta_K$$

$$+ \frac{9}{32\pi}(S_{14}\sin 2\theta_l + S_{15}\sin\theta_l)\sin\theta_K\cos\phi$$

$$+ \frac{9}{32\pi}(S_{16}\sin\theta_l + S_{17}\sin 2\theta_l)\sin\theta_K\sin\phi\,,$$



Dispersion relation for non-local states

$$\Delta Y_{c\bar{c}}(q^2) = \frac{(q^2 - {q^2}_0)}{\pi} \int_{q^2_{min}}^{\infty} ds \frac{s \cdot Im\left[Y_{c\bar{c}}(s)\right]}{(s - {q^2}_0)(s - q^2 - i\epsilon)}$$

$$\equiv \frac{(q^2 - {q^2}_0)}{\pi} \int_{q^2_{min}}^{\infty} ds \frac{\rho_{c\bar{c}}(s)}{(s - {q^2}_0)(s - q^2 - i\epsilon)},$$

$$\Delta Y^{1P}_{c\bar{c}}(q^2) = \sum_{j=\mathrm{J}/\psi \ldots \psi(4415)} \eta_j e^{i\delta_j} \frac{(q^2 - {q^2}_0)}{(m_j^2 - {q^2}_0)} A_j^{res}(q^2), \quad A_j^{res}(q^2) = \frac{m_j \Gamma_{0j}}{(m_j^2 - q^2) - i m_j \Gamma_j(q^2)},$$

$$\Delta Y^{2P}_{c\bar{c}}(q^2) = \sum_{j=\mathrm{DD},\mathrm{D^*D^*},\mathrm{DD^*}} \eta_j e^{i\delta_j} A_j^{2P}(q^2), \quad A_j^{2P}(q^2) = \frac{(q^2 - {q^2}_0)}{\pi} \int_{q^2_{min}}^{\infty} ds \frac{\hat{\rho}_j(s)}{(s - {q^2}_0)(s - q^2 - i\epsilon)},$$

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Dispersion relation for non-local states

$$\hat{\rho}_{j1j2}(s) \propto \sqrt{\frac{\lambda(s, m_{j1}^2, m_{j2}^2)}{s}}^{\,2L+1},$$

$$\hat{\rho}_{\mathrm{DD}}(s) \equiv \hat{\rho}_{\mathrm{D}}(s) = \left(1 - \frac{4m_{\mathrm{D}}^2}{s}\right)^{3/2}, \qquad \hat{\rho}_{\mathrm{D^*D^*}}(s) \equiv \hat{\rho}_{\mathrm{D^*}}(s) = \left(1 - \frac{4m_{\mathrm{D^*}}^2}{s}\right)^{3/2}$$

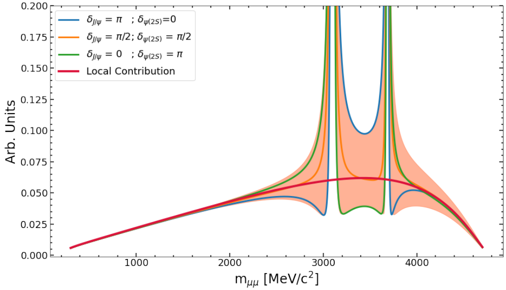
$$\hat{\rho}_{\mathrm{DD^*}}(s) \equiv \hat{\rho}_{\overline{\mathrm{D}}}(s) = \left(1 - \frac{4m_{\overline{\mathrm{D}}}^2}{s}\right)^{1/2}$$

$$\Delta Y_{\mathrm{c\bar{c}}}^{2P}(q^2) = \eta_{\overline{\mathrm{D}}} e^{i\delta_{\overline{\mathrm{D}}}} h_S\left(m_{\overline{\mathrm{D}}}, q^2\right) + \sum_{j=\mathrm{D},\mathrm{D^*}} \eta_j e^{i\delta_j} h_P\left(\mathrm{m}_j, q^2\right),$$

$$h_S\left(m, q^2\right) = 2 - G\left(1 - \frac{4m^2}{q^2}\right), \qquad h_P\left(m, q^2\right) = \frac{2}{3} + \left(1 - \frac{4m^2}{q^2}\right) h_S\left(m, q^2\right),$$

$$G(y) = \sqrt{|y|}\left\{\Theta(y)\left[\ln\left(\frac{1+\sqrt{y}}{1-\sqrt{y}}\right) - i\pi\right] + 2\,\Theta(-y)\arctan\left(\frac{1}{\sqrt{-y}}\right)\right\}.$$

Importance of measuring interference

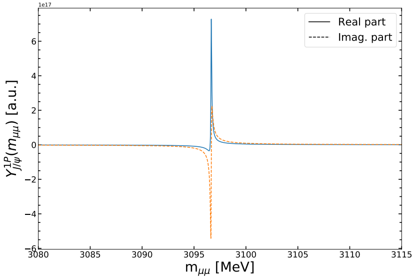


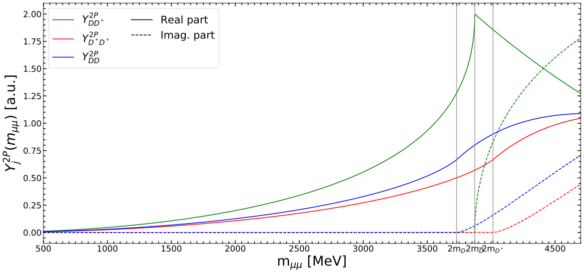
- Interference can mimic new physics in C_9.
- In order to determine precisely the couplings involved,
  the non-local contributions need to be understood.

non-local state description

- 1P states are narrow resonances described using relativistic Breit-Wigers.
- 2P state amplitudes calculated in [Cornella et al.] shown below
- Magnitude and phase of non-local states are fit parameters

$q^2 \equiv m^2_{\mu\mu}$





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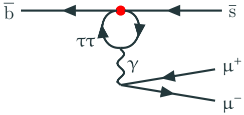
τ Enhancement

Possible to link $\mathrm{b} \to \mathrm{c}\ell\overline{\nu}_\ell$ and $\mathrm{b} \to \mathrm{s}\ell^+\ell^-$ measurements within SMEFT
[Crivellin et al.], [Capdevila et al.].

For a generic flavour structure and in the absence of $b \to s\nu\nu$[1]

$$C_9^{\tau\tau} = -C_{10}^{\tau\tau} \approx \frac{-2V_{\mathrm{cb}}}{V_{\mathrm{tb}}V_{\mathrm{ts}}^*}\frac{\pi}{\alpha}\left(\sqrt{R_{D(*)}/R_{D(*)}^{SM}} - 1\right).$$



Here $C_i^{\tau\tau}$ describes the presence of tau-loop contribution which through radiative effects anturally produces a lepton universal

$$C_9^U = \frac{\alpha}{3\pi} log\left(\frac{\Lambda^2}{\mu_b^2}\right) C_9^{\tau\tau},$$

where Λ is the scale of new physics. [Algueró et al.]

[1] Limits of $< 10^{-5}$ from [BaBar][BELLE] [BELLE II]

Local hadronic effects z-expansion

Exploit analyticity and interpolate to full q^2

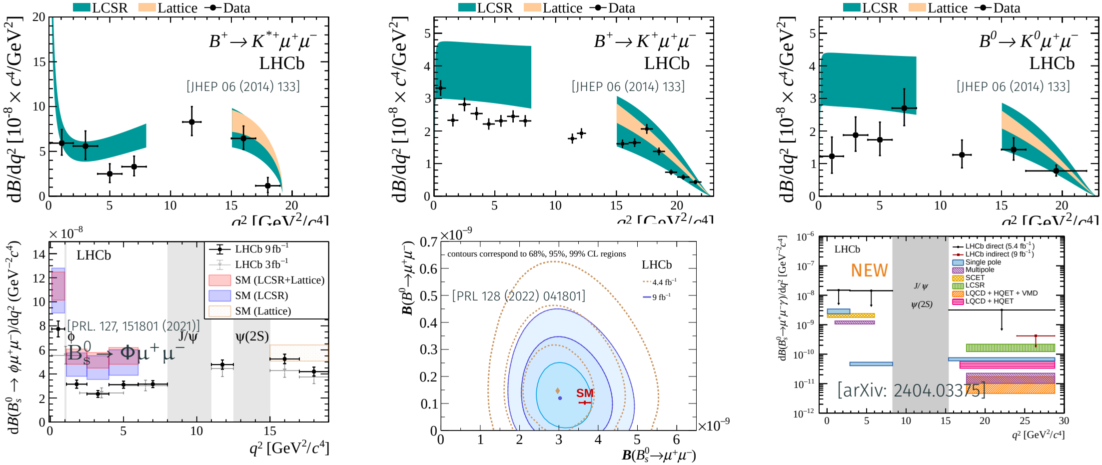
$$\mathcal{F}_\lambda(q^2) = \frac{1}{q^2 - m_{B_s^*}^2} \sum_{k=0}^{N} a_\lambda z^k$$

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}},$$

with N=2, $t_+ = (m_B^2 + m_M^2)$ and t_0 is a choice of the origin.

Branching Fraction measurments

Observed tensions can be explained by a NP shift in C_9 or $C_{9/10}$.



SM predictions limited by hadronic uncertainties

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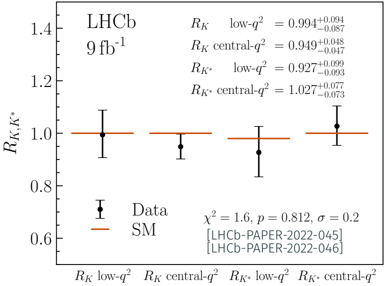
Lepton Flavour Universality Tests in $b \to s\ell^+\ell^-$



Ratios of the form:

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\cong} 1,$$

free from QCD uncertainties and O(1%) QED corrections.

Measurement at LHCb performed using a double ratio with the resonant mode cancels exp. systematics

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B \to K^{(*)}e^+e^-)}{\mathcal{B}(B \to K^{(*)}J/\psi(\to e^+e^-))}$$

Latest and most precise simultaneous measurement of R_K and R_{K^*} compatible with SM. Does not exclude lepton flavour universal New Physics

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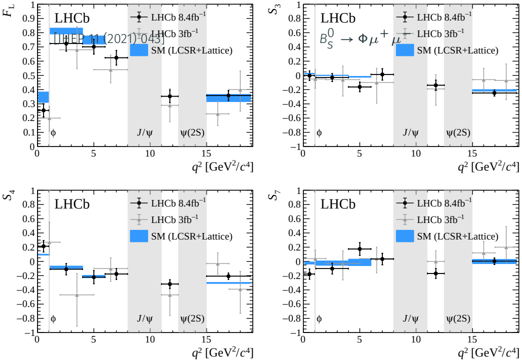
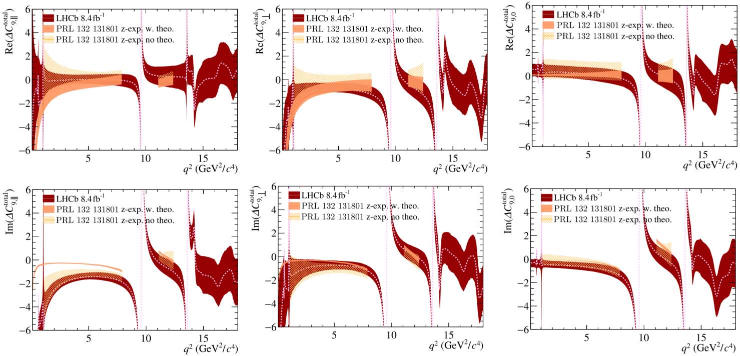
Angular plots



- Angular definition same for $\mathrm{B_s^0}$ and $\overline{\mathrm{B}}{}_\mathrm{s}^0$ since no self tagging of decay.
- Therefore, can't access P_5' or A_{FB}
- The decay of $B_S^0 \to \Phi\mu^+\mu^-$ also shows small tensions with SM in combined fits

Compatibility of $B^0 \to K^{*0}\mu^+\mu^-$ analyses



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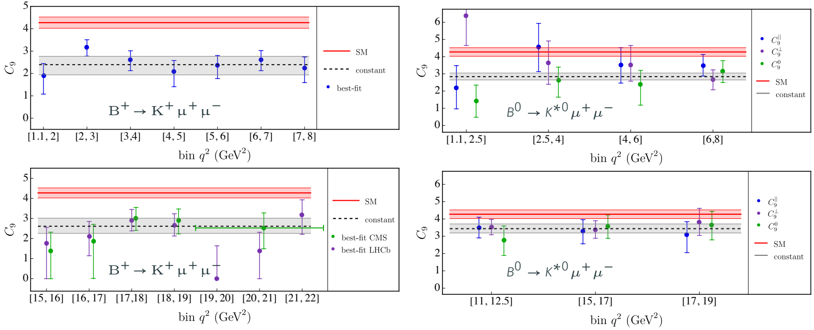
Determination of a q^2 dependent C_9^μ

[Marzia Bordone, Gino Isidori, Sandro Mächler, Arianna Tinari]



- Data driven estimation of q^2 dependent C_9^μ incl. non-local effects.
- No sizable q^2 dependence observed which would arise from unaccounted for charm-loop effects
- Discrepancy with SM consistent with short-distance effect of non-SM origin

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

$$\mathcal{O}_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu\, a}, \qquad \mathcal{O}'_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_L b) G^{\mu\nu\, a},$$

$$\mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu), \qquad \mathcal{O}'_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu),$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu), \qquad \mathcal{O}'_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \gamma_5 \mu),$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{\mu}\mu), \qquad \mathcal{O}'_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b)(\bar{\mu}\mu),$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{\mu}\gamma_5 \mu), \qquad \mathcal{O}'_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b)(\bar{\mu}\gamma_5 \mu),$$

*Altmannshofer et al.

$$A_{\perp L,R} = N\sqrt{2}\lambda^{1/2}\left[\left[(C_9^{\text{eff}} + C_9^{\text{eff}\prime}) \mp (C_{10}^{\text{eff}} + C_{10}^{\text{eff}\prime})\right]\frac{V(q^2)}{m_B + m_{K*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} + C_7^{\text{eff}\prime})T_1(q^2)\right],$$

$$A_{\parallel L,R} = -N\sqrt{2}(m_B^2 - m_{K*}^2)\left[\left[(C_9^{\text{eff}} - C_9^{\text{eff}\prime}) \mp (C_{10}^{\text{eff}} - C_{10}^{\text{eff}\prime})\right]\frac{A_1(q^2)}{m_B - m_{K*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} - C_7^{\text{eff}\prime})T_2(q^2)\right],$$

$$A_{0L,R} = -\frac{N}{2m_{K*}\sqrt{q^2}}\left\{\left[(C_9^{\text{eff}} - C_9^{\text{eff}\prime}) \mp (C_{10}^{\text{eff}} - C_{10}^{\text{eff}\prime})\right] \times \left[(m_B^2 - m_{K*}^2 - q^2)(m_B + m_{K*})A_1(q^2) - \lambda\frac{A_2(q^2)}{m_B + m_{K*}}\right] + 2m_b(C_7^{\text{eff}} - C_7^{\text{eff}\prime})\left[(m_B^2 + 3m_{K*}^2 - q^2)T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K*}^2}T_3(q^2)\right]\right\},$$

$$A_t = \frac{N}{\sqrt{q^2}}\lambda^{1/2}\left[2(C_{10}^{\text{eff}} - C_{10}^{\text{eff}\prime}) + \frac{q^2}{m_\mu}(C_P - C_P')\right]A_0(q^2),$$

$$A_S = -2N\lambda^{1/2}(C_S - C_S')A_0(q^2),$$

where

$$N = V_{tb}V_{ts}^*\left[\frac{G_F^2\alpha^2}{3\cdot 2^{10}\pi^5 m_B^3}q^2\lambda^{1/2}\beta_\mu\right]^{1/2},$$

*Altmannshofer et al.

$$J_1^s = \frac{(2+\beta_\mu^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right] + \frac{4m_\mu^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}\right),$$

$$J_1^c = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R*})\right] + \beta_\mu^2|A_S|^2,$$

$$J_2^s = \frac{\beta_\mu^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right],$$

$$J_2^c = -\beta_\mu^2\left[|A_0^L|^2 + (L\to R)\right],$$

$$J_3 = \frac{1}{2}\beta_\mu^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + (L\to R)\right],$$

$$J_4 = \frac{1}{\sqrt{2}}\beta_\mu^2\left[\mathrm{Re}(A_0^L A_\parallel^{L*}) + (L\to R)\right],$$

$$J_5 = \sqrt{2}\beta_\mu\left[\mathrm{Re}(A_0^L A_\perp^{L*}) - (L\to R) - \frac{m_\mu}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^* + A_\parallel^R A_S^*)\right],$$

$$J_6^s = 2\beta_\mu\left[\mathrm{Re}(A_\parallel^L A_\perp^{L*}) - (L\to R)\right],$$

$$J_6^c = 4\beta_\mu\frac{m_\mu}{\sqrt{q^2}}\mathrm{Re}\left[A_0^L A_S^* + (L\to R)\right],$$

$$J_7 = \sqrt{2}\beta_\mu\left[\mathrm{Im}(A_0^L A_\parallel^{L*}) - (L\to R) + \frac{m_\mu}{\sqrt{q^2}}\mathrm{Im}(A_\perp^L A_S^* + A_\perp^R A_S^*)\right],$$

$$J_8 = \frac{1}{\sqrt{2}}\beta_\mu^2\left[\mathrm{Im}(A_0^L A_\perp^{L*}) + (L\to R)\right],$$

$$J_9 = \beta_\mu^2\left[\mathrm{Im}(A_\parallel^{L*} A_\perp^L) + (L\to R)\right].$$

*Altmannshofer et al.

$$
\begin{aligned}
J(q^2, \theta_l, \theta_{K^*}, \phi) = {} & J_1^s \sin^2\theta_{K^*} + J_1^c \cos^2\theta_{K^*} + (J_2^s \sin^2\theta_{K^*} + J_2^c \cos^2\theta_{K^*}) \cos 2\theta_l \\
& + J_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + J_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi \\
& + J_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi \\
& + (J_6^s \sin^2\theta_{K^*} + J_6^c \cos^2\theta_{K^*}) \cos\theta_l + J_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi \\
& + J_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + J_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi \,.
\end{aligned}
$$

*Altmannshofer et al.