A New Tool for Detecting BSM Physics in $B \to K^* \ell^+ \ell^-$ Decays

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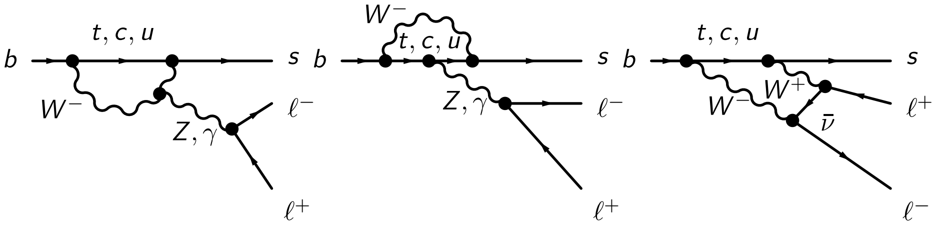
Introduction

- The semileptonic decay $B \to K^* \ell^+ \ell^-$ is of particular relevance in new physics searches since it involves flavor-changing neutral current transitions (FCNC) and is forbidden in the standard model at tree level. Its angular distributions gives access to observables that are sensitive to New Physics (NP).
- This decay is being intensively studied by HEP experiments and their results show some tensions with the SM predictions.
- A $B \to K^* \ell^+ \ell^-$ decay generator with NP contributions which cover all possible dimension 6 operators has been implemented in `EvtGen`, based on the SM variant. `EvtGen` is a particle generator framework which provides convenient tools to implement such complex decays.
- A 4-D maximum likelihood unbinned fit has been implemented and it shows excellent sensitivity to NP contributions (in absence of backgrounds).
- There are the strong difficulties in reliably computing all of the possible hadronic effects, such as the hadronic form factor, resonance effects, and non-factorizable contributions. Extracted parameters in the di-electron and di-muon modes, according to our study, are biased due to such effects but the bias is correlated between the modes and cancels in a Δ observable, a parameter difference between the flavor modes. The Δ observable is the only possible approach to definitively distinguish between these effects and reliably establish NP with high statistics Belle II measurements.
- The following content is described in the Snowmass2021 contribution: "A New Tool for Detecting BSM Physics in $B \to K^* \ell\ell$ Decays" [arXiv:2203.06827].

SM lowest-order contributions



At the lowest-order in the SM, the process $b \to s\ell\ell$ results from interference of the γ/Z penguins and the W^-W^+ box diagrams.

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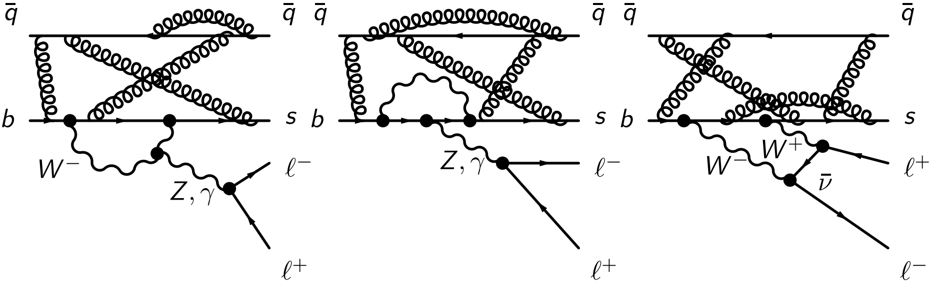


At the lowest-order in the SM, the process $b \to s\ell\ell$ results from interference of the γ/Z penguins and the W^-W^+ box diagrams.

In addition, these complex quark-level processes are shrouded by the long-distance QCD interactions and non-factorizable contributions and thus requires evaluation of the hadronic form factors.

The matrix element with NP contributions

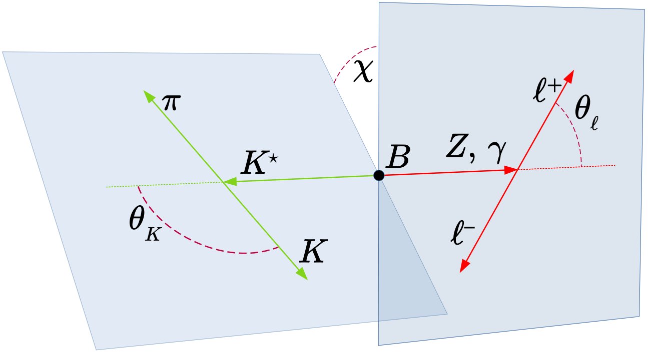
The matrix element is adopted from JHEP **01**, 019 (2009) and it covers all possible dimension 6 NP operators:

$$
\begin{aligned}
\mathcal{M} = & \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \Big\{ \Big[\langle K\pi | \bar{s}\gamma^\mu (C_9^{\text{eff}} P_L + C_9'^{\text{eff}} P_R) b | \bar{B} \rangle \\
& - \frac{2m_b}{q^2} \langle K\pi | \bar{s} i \sigma^{\mu\nu} q_\nu (C_7^{\text{eff}} P_R + C_7'^{\text{eff}} P_L) b | \bar{B} \rangle \Big] (\bar{\ell}\gamma_\mu \ell) \\
& + \langle K\pi | \bar{s}\gamma^\mu (C_{10}^{\text{eff}} P_L + C_{10}'^{\text{eff}} P_R) b | \bar{B} \rangle (\bar{\ell}\gamma_\mu \gamma_5 \ell) \\
& + \langle K\pi | \bar{s} (C_S P_R + C_S' P_L) b | \bar{B} \rangle (\bar{\ell}\ell) + \langle K\pi | \bar{s} (C_P P_R + C_P' P_L) b | \bar{B} \rangle (\bar{\ell}\gamma_5 \ell) \Big\}.
\end{aligned}
$$

C_7', C_9', C_{10}', C_S, C_P, C_S', and C_P' coefficients correspond to NP contributions. Scalar and pseudo-scalar contributions vanish in the SM limit.

There are hints of additional contributions to C_9 and C_{10} in $B \to K^* \ell^+ \ell^-$ data.

Kinematic variables for angular analysis



The kinematics of the decay are described by 4 parameters:

$$\frac{\Gamma(B \to K^* \ell^+ \ell^-)}{\mathrm{d}q^2\ \mathrm{d}\cos\theta_\ell\ \mathrm{d}\cos\theta_K\ \mathrm{d}\chi}$$

in the $\Gamma_{K^*} \to 0$ limit. θ_ℓ and θ_K are defined with respect to the B momentum in the corresponding rest frames. q^2 is the invariant mass squared of the leptons.

The hadronic currents

Hadronic currents in the matrix element are parametrized in terms of hadronic form factors:

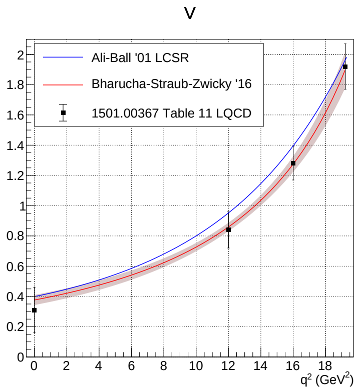
$$\langle \bar{K}^*(k)|\bar{s}\gamma_\mu(1\mp\gamma_5)b|\bar{B}(p)\rangle = \mp i\epsilon^*_\mu(m_B+m_{K^*})A_1(q^2) \pm i(2p-q)_\mu(\epsilon^*\cdot q)\,\frac{A_2(q^2)}{m_B+m_{K^*}}$$
$$\pm\, iq_\mu(\epsilon^*\cdot q)\,\frac{2m_{K^*}}{q^2}\,\left[A_3(q^2)-A_0(q^2)\right] + \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho k^\sigma\,\frac{2V(q^2)}{m_B+m_{K^*}}, \quad (17)$$
$$\text{with } A_3(q^2) = \frac{m_B+m_{K^*}}{2m_{K^*}}A_1(q^2) - \frac{m_B-m_{K^*}}{2m_{K^*}}A_2(q^2) \text{ and } A_0(0)=A_3(0); \quad (18)$$

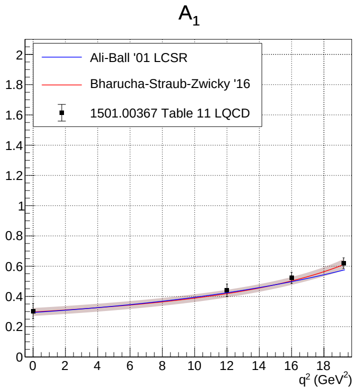
$$\langle \bar{K}^*(k)|\bar{s}\sigma_{\mu\nu}q^\nu(1\pm\gamma_5)b|\bar{B}(p)\rangle = i\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho k^\sigma\,2T_1(q^2)$$
$$\pm\, T_2(q^2)\left[\epsilon^*_\mu(m_B^2-m_{K^*}^2)-(\epsilon^*\cdot q)\,(2p-q)_\mu\right] \pm T_3(q^2)(\epsilon^*\cdot q)\left[q_\mu - \frac{q^2}{m_B^2-m_{K^*}^2}\,(2p-q)_\mu\right], \quad (19)$$

with $T_1(0)=T_2(0)$;

$$\langle \bar{K}^*(k)|\bar{s}(1\mp\gamma_5)b|\bar{B}(p)\rangle = \pm i(\epsilon^*\cdot q)\,\frac{2m_{K^*}}{m_b+m_s}A_0(q^2)\,. \quad (20)$$

A. Bharucha, D. M. Straub and R. Zwicky, JHEP 1608, 098 (2016) [arXiv:1503.05534]. This parametrization is also know as the ABSZ form factor parameterization. Joint fit to the LCSR and LQCD calculations.





The old default form factors in `EvtGen` (blue line) still look good enough.

Wilson coefficients

From W. Altmannshofer, P. Ball, A. Bharucha et al., JHEP **01**,(2009) 019

$$C_7^{\text{eff}} = \frac{4\pi}{\alpha_s} C_7 - \frac{1}{3} C_3 - \frac{4}{9} C_4 - \frac{20}{3} C_5 - \frac{80}{9} C_6 \,,$$

$$C_8^{\text{eff}} = \frac{4\pi}{\alpha_s} C_8 + C_3 - \frac{1}{6} C_4 + 20 C_5 - \frac{10}{3} C_6 \,,$$

$$C_9^{\text{eff}} = \frac{4\pi}{\alpha_s} C_9 + Y(q^2) \,,$$

$$C_{10}^{\text{eff}} = \frac{4\pi}{\alpha_s} C_{10} \,, \qquad C_{7,8,9,10}^{\prime,\text{eff}} = \frac{4\pi}{\alpha_s} C'_{7,8,9,10} \,,$$

$$\begin{aligned} Y(q^2) = {} & h(q^2, m_c) \left(\frac{4}{3} C_1 + C_2 + 6 C_3 + 60 C_5 \right) \\ & - \frac{1}{2} h(q^2, m_b) \left(7 C_3 + \frac{4}{3} C_4 + 76 C_5 + \frac{64}{3} C_6 \right) \\ & - \frac{1}{2} h(q^2, 0) \left(C_3 + \frac{4}{3} C_4 + 16 C_5 + \frac{64}{3} C_6 \right) \\ & + \frac{4}{3} C_3 + \frac{64}{9} C_5 + \frac{64}{27} C_6 \,. \end{aligned}$$

$$h(q^2, m_q) = -\frac{4}{9} \left(\ln \frac{m_q^2}{\mu^2} - \frac{2}{3} - z \right) - \frac{4}{9} (2 + z) \sqrt{|z - 1|} \times \begin{cases} \arctan \dfrac{1}{\sqrt{z - 1}} & z > 1 \\ \ln \dfrac{1 + \sqrt{1 - z}}{\sqrt{z}} - \dfrac{i\pi}{2} & z \le 1 \end{cases}$$

Older Belle II `EvtGen` simulation used the hardcoded coefficients C_7, C_9, and C_{10} (implemented by Jeffrey Berryhill in the mid-2000s) which are based on the work A. Ali, E. Lunghi, C. Greub and G. Hiller, "Improved model independent analysis of semileptonic and radiative rare B decays," Phys. Rev. D **66**, 034002 (2002), which may be outdated.

With the new generator we can easily modify the Wilson coefficients using the `EvtGen` card file and thus study sensitivity to NP contributions.

Resonance effects and C_9

Currently resonances are added at the amplitude level to C_9 through *h*-function:

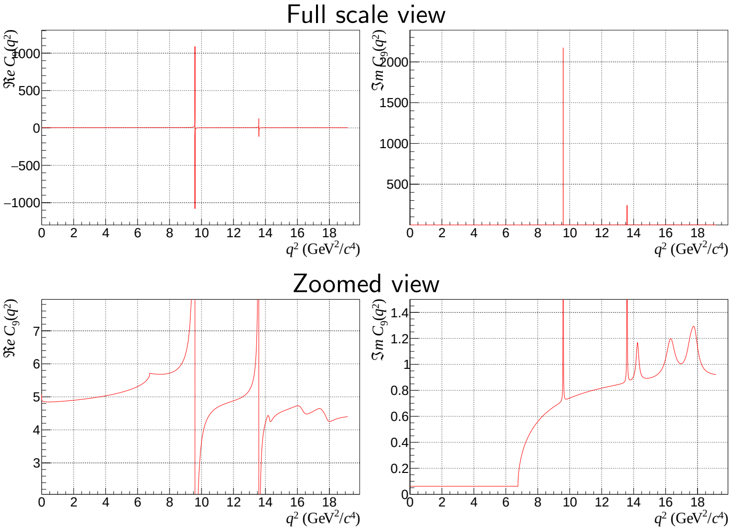
$$h(m_c, q^2) \to h(m_c, q^2) - \frac{3\pi}{\alpha^2} \sum_{V=J/\psi,\psi',..} \frac{m_V \mathrm{Br}(V \to \ell^+\ell^-)\Gamma^V_{\mathrm{total}}}{q^2 - m_V^2 + i m_V \Gamma^V_{\mathrm{total}}} . \quad (34)$$

In future we are planing to use the dispersion relation approach:

$$\mathrm{Im}\, h(m_c, q^2)_{\mathrm{Reso}} = \frac{\pi}{3} \mathrm{R}^{c\bar{c}}_{\mathrm{had}}(q^2) \quad (31)$$

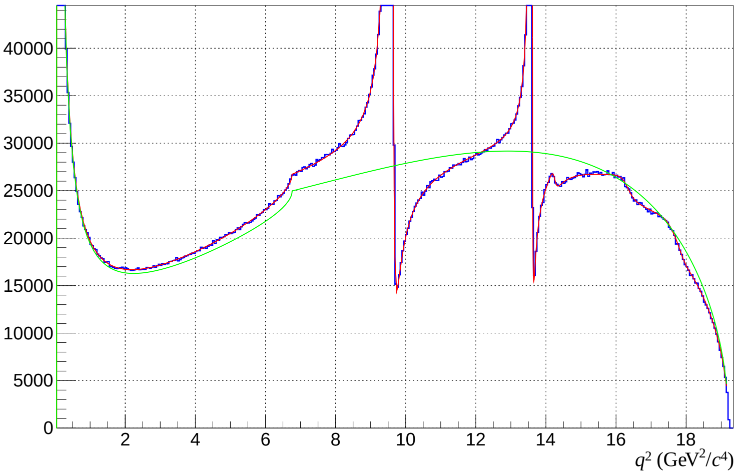
$$\mathrm{Re}\, h(m_c, q^2)_{\mathrm{Reso}} = -\frac{8}{9} \ln \frac{m_c}{m_b} - \frac{4}{9} + \frac{q^2}{3} P \int_{4m_D^2/m_b^2}^{\infty} \frac{\mathrm{R}^{c\bar{c}}_{\mathrm{had}}(q'^2)}{q'^2(q'^2 - q^2)} dq'^2 . \quad (32)$$

Effect of $c\bar{c}$ resonances on C_9



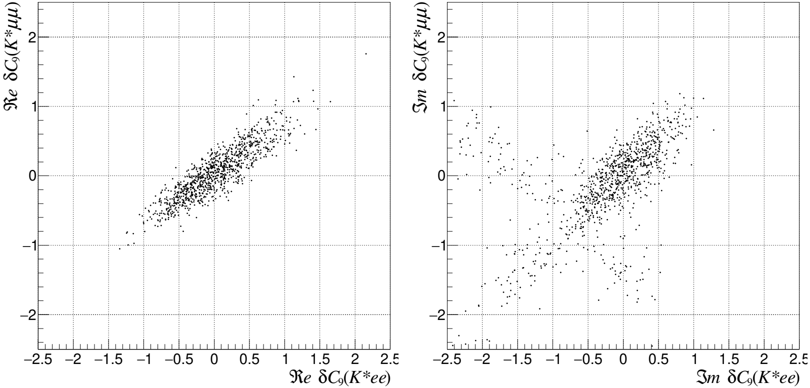
$C_9(q^2)$ is significantly modified in the presence of resonances.

EvtGen and the likelihood comparison in $\bar{B} \to \bar{K}^* \mu^+ \mu^-$



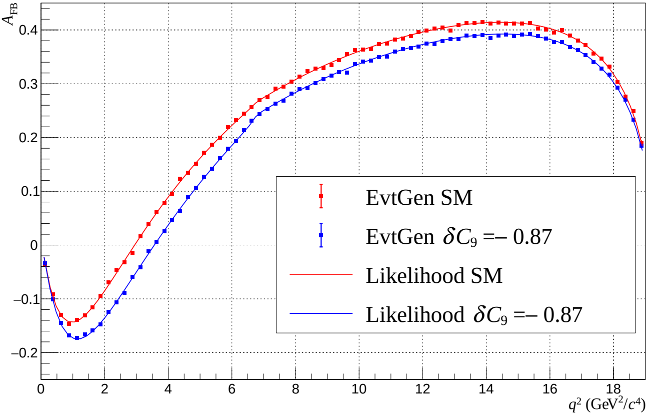
The resonances affect q^2 areas much larger than their widths. The solid lines show the integrated likelihood with and without $c\bar{c}$ resonances. The histogram is the EvtGen result.

Δ-observable to constrain NP effects



In each fit hadronic form factors are varied within their uncertainties simultaneously in the di-electron and di-muon modes. A clear correlation between modes is visible. The $\Delta C_9 = \delta C_9(\mu\mu) - \delta C_9(ee)$ uncertainty is smaller than the uncertainties caused by unknown form factors in $\delta C_9(ee)$ and $\delta C_9(\mu\mu)$ variables alone and thus might be more sensitive to NP contributions than single modes alone.

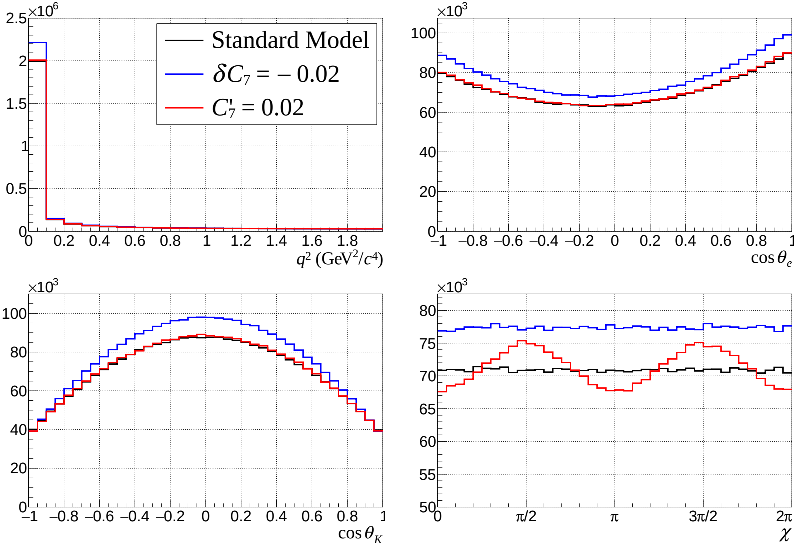
Integrated angular observable and EvtGen result



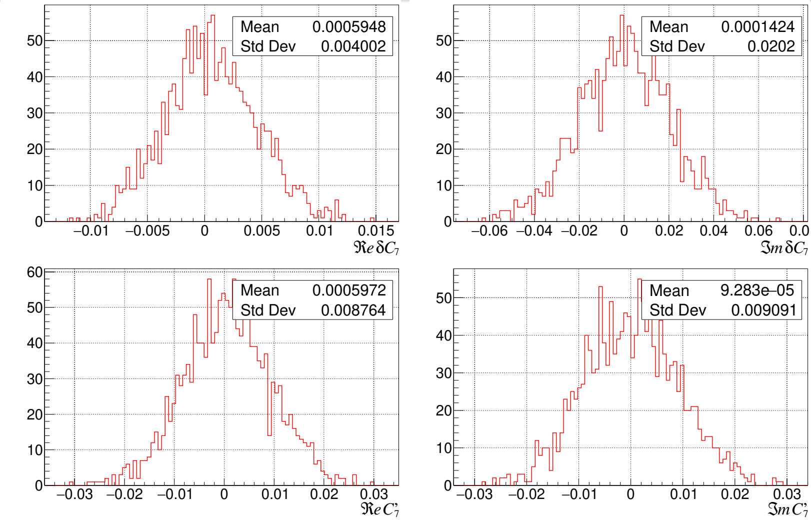
Here, $\delta C_9 = C_9^{NP} - C_9^{SM} = -0.87 \pm 0.18$ is taken from "New Physics in Rare B Decays after Moriond 2021" by Altmannshofer and Stangl. Note the shifts for this δC_9^{NP}. Similar effect is observed in other variables, e.g. S_5, so ΔA_{FB} and ΔS_5 both have to be nonzero to verify the presence of NP.

Effect of NP in δC_7 and C_7' on q^2 and angular observables

$\bar{B} \to \bar{K}^* e^+ e^-$ process

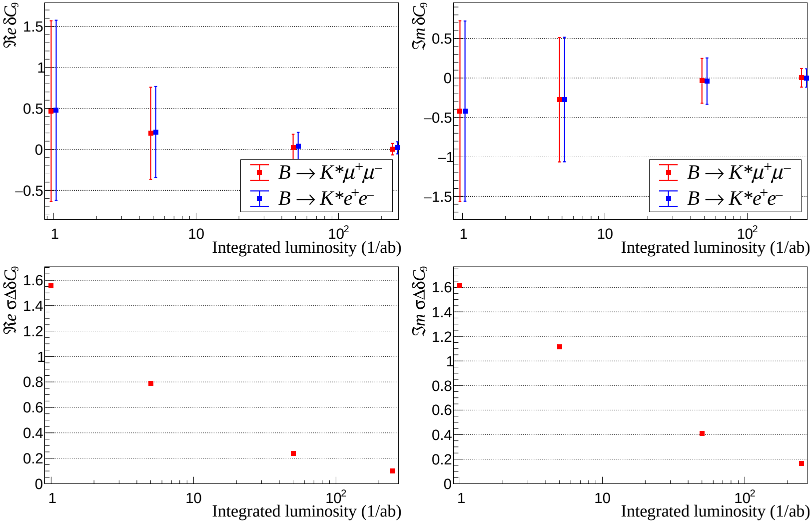


Sensitivity to δC_7 and C_7' with likelihood fit and 50/ab



The 4-D likelihood fit shows excellent sensitivity: based on the di-electron mode σ_{C_7} is about 1.5 and 6.5 % of $|C_7^{SM}|$ for the real and imaginary parts and 3% for C_7'.

ΔC_9 sensitivity projection with Belle II statistics



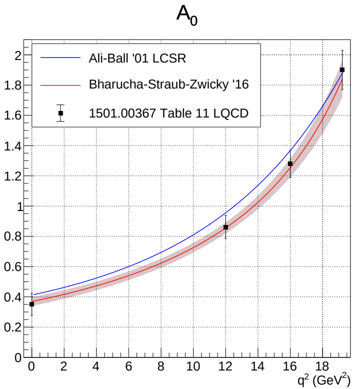
Fits are performed with $q^2 > 1\,\mathrm{GeV}^2/c^4$ and 0.25 GeV^2/c^4 veto windows around J/ψ and $\psi(2S)$ regions assuming 25% selection efficiency.

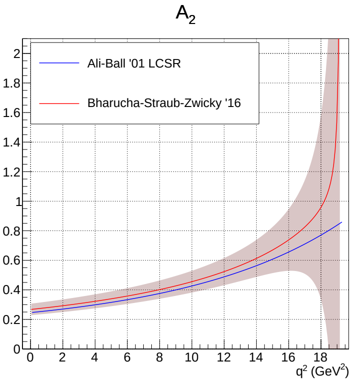
Conclusions

- A new model implemented in the `EvtGen` framework enables evaluation of the experimental sensitivity to various NP contributions (can be set by the user in the card file) in $B \to K^* \ell^+ \ell^-$ decays.
- With the unbinned maximum likelihood fit we can directly extract short-distance contributions in terms of the Wilson coefficients with excellent sensitivity.
- The Δ variables are a powerful tool to mitigate the hadronic uncertainties and opens possibility of searching for NP effects with the anticipated Belle II data.
- More information can be found in the Snowmass2021 contribution "A New Tool for Detecting BSM Physics in $B \to K^* \ell\ell$ Decays" [arXiv:2203.06827]. It will be updated as a Physical Review D paper.
- Plans:
  - More sensitivity tests with various combinations of the Wilson coefficients.
  - Integrate the generator into the official `EvtGen` codebase.

Backup slides

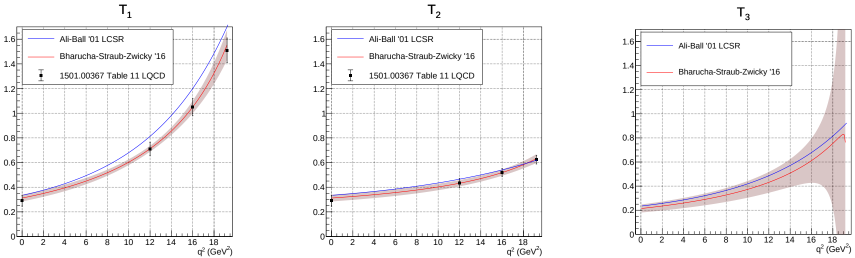
Form factors





The finite width of K^* is taken into account and thus the visible singularity at the kinematic endpoint is never reached.

Tensor form factors



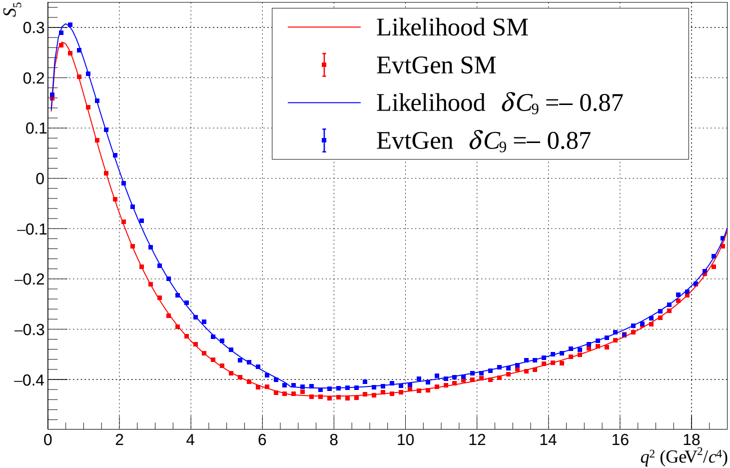
A_{12} and T_{23} were parameterized and the form factors A_2 and T_3 were extracted using the expression:

$$A_{12} = \frac{(m_B + m_{K^*})^2 \left(m_B^2 - m_{K^*}^2 - q^2\right) A_1 - \lambda(q^2) A_2}{16 m_B m_{K^*}^2 (m_B + m_{K^*})}$$

$$T_{23} = \frac{\left(m_B^2 - m_{K^*}^2\right)\left(m_B^2 + 3m_{K^*}^2 - q^2\right) T_2 - \lambda(q^2) T_3}{8 m_B m_{K^*}^2 (m_B - m_{K^*})}.$$

Here, $m_{K^*}^2 = (p_K + p_\pi)^2$ and it very important to take into account the finite width of K^* otherwise the singularity appears in the physical region.

Angular observables



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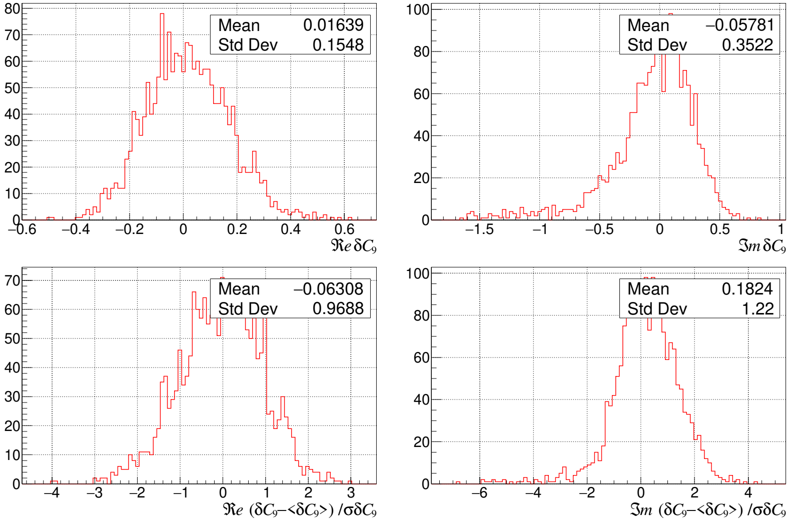
Sensitivity to δC_9 with likelihood fit and 50/ab



Based on the di-mion mode σ is about 3 and 7 % of $|C_9^{SM}|$ for the real and imaginary parts.