New MC tool and analysis method for $B \to K^* \ell^+ \ell^-$ decays

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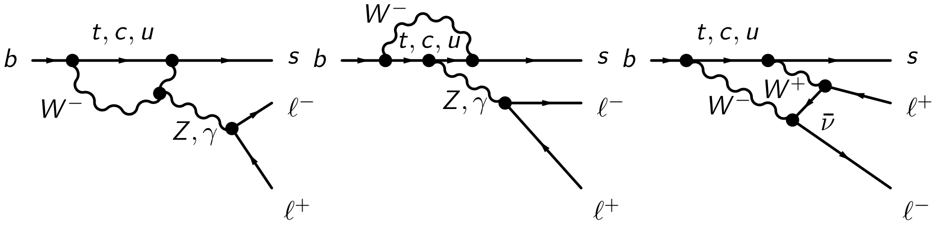
Introduction

- 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 NP.
- A $B \to K^* \ell^+ \ell^-$ decay generator with New Physics 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).
- A Δ-observable between the di-electron and di-muon modes should mitigate the uncertainties from the hadronic form factor, resonance effects, and non-factorizable contributions.
- 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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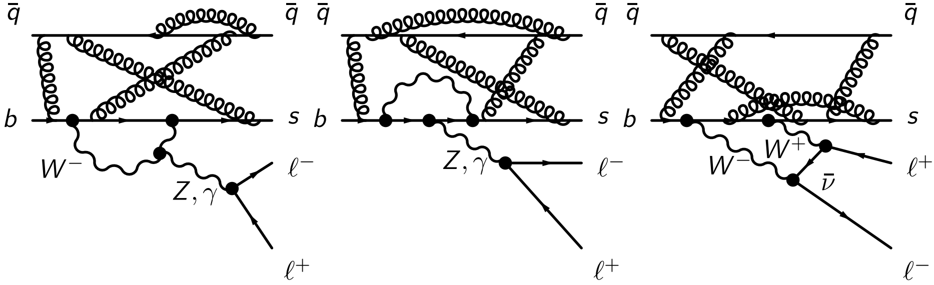


At the lowest-order in the SM, the process $b \to s\ell\ell$ results from interference of the γ/Z penguins and the W^-W^+ box diagrams.

In addition, this complex at the quark level process is shrouded by the QCD interactions and non-factorizable contributions and thus requires evaluation of the hadronic form factors.

The matrix element suggested by Rusa Mandal & Rahul Sinha from JHEP **01**, 019 (2009) covers all possible dimension 6 NP operators.

nian (1) for the decay $B \to K^*(\to K\pi)\ell^+\ell^-$ as

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

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.

The hadronic currents

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

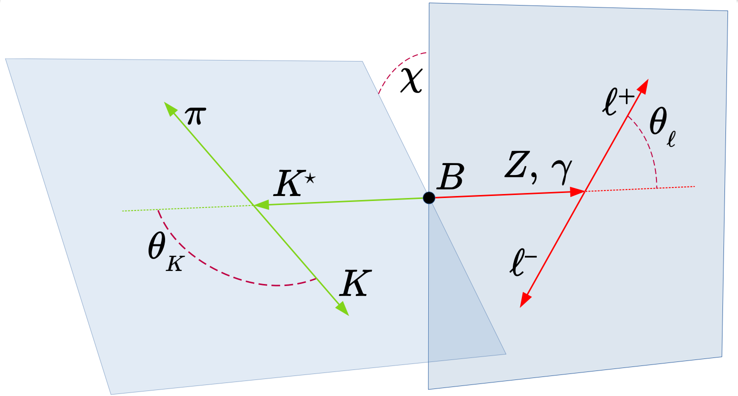
$$\langle \bar{K}^*(k)|\bar{s}\gamma_\mu(1\mp\gamma_5)b|\bar{B}(p)\rangle = \mp i\epsilon^*_\mu(m_B+m_{K^*})A_1(q^2) \pm i(2p-q)_\mu(\epsilon^*\cdot q)\,\frac{A_2(q^2)}{m_B+m_{K^*}}$$
$$\pm\, iq_\mu(\epsilon^*\cdot q)\,\frac{2m_{K^*}}{q^2}\,\left[A_3(q^2)-A_0(q^2)\right] + \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho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

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

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

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

Decay kinematics



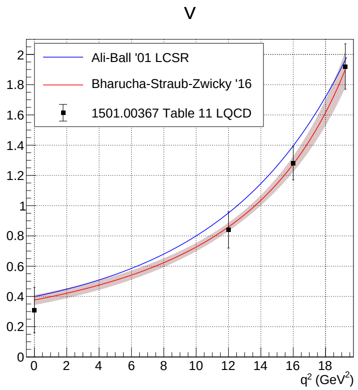
The kinematics of the decay are described by 4 parameters:

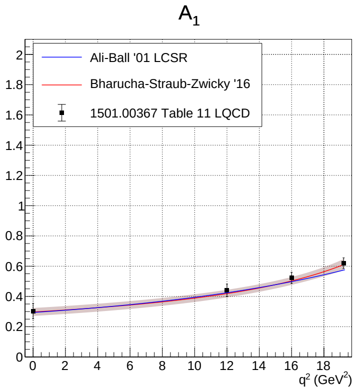
$$\frac{\Gamma(B \to K^*\ell^+\ell^-)}{dq^2 \; d\cos\theta_\ell \; d\cos\theta_K \; d\chi}$$

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.

Updated hadronic form factors

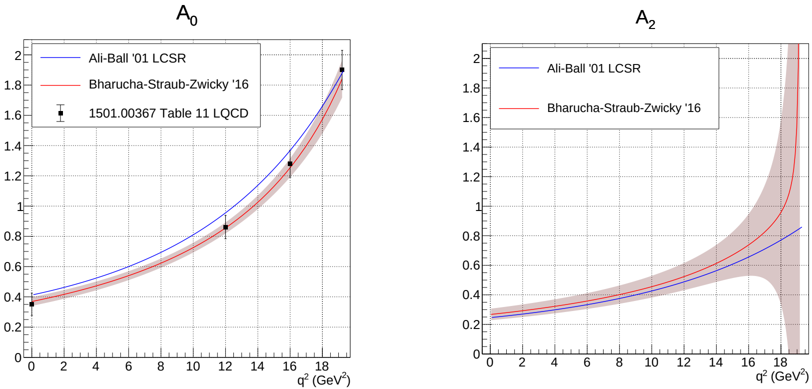
A. Bharucha, D. M. Straub and R. Zwicky, JHEP 1608, 098 (2016) [arXiv:1503.05534]. This parametrization is also know as the ABSZ form factor parameterization. Joint fit to the LCSR and LQCD calculations.





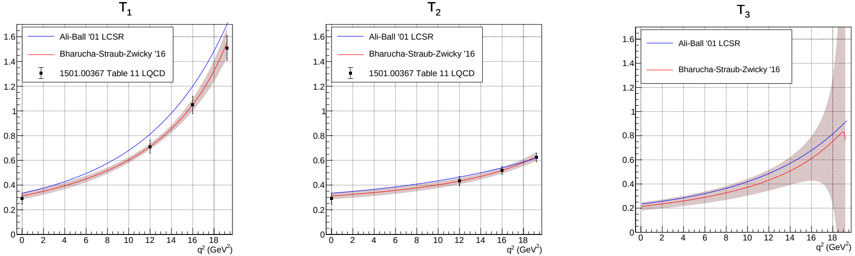
The old default form factors in EvtGen (blue line) still look good enough.

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:

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

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

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.

Wilson coefficients

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

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

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

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

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

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

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

Currently Belle II simulation uses the 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), so it might be that this is a little bit outdated calculation.

Resonance effects and C_9

Dispersion relation (in progress):

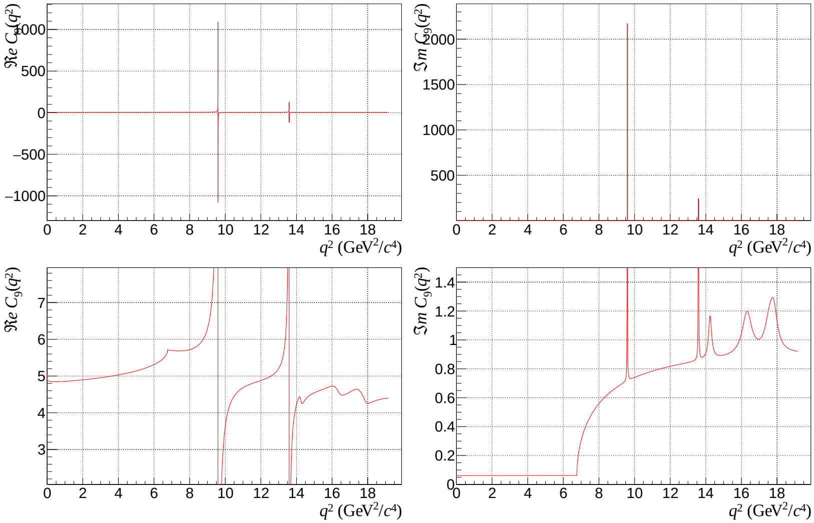
$$\mathrm{Im}\, h(m_c, q^2)_{\mathrm{Reso}} = \frac{\pi}{3} \mathrm{R}^{c\bar{c}}_{\mathrm{had}}(q^2) \tag{31}$$

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

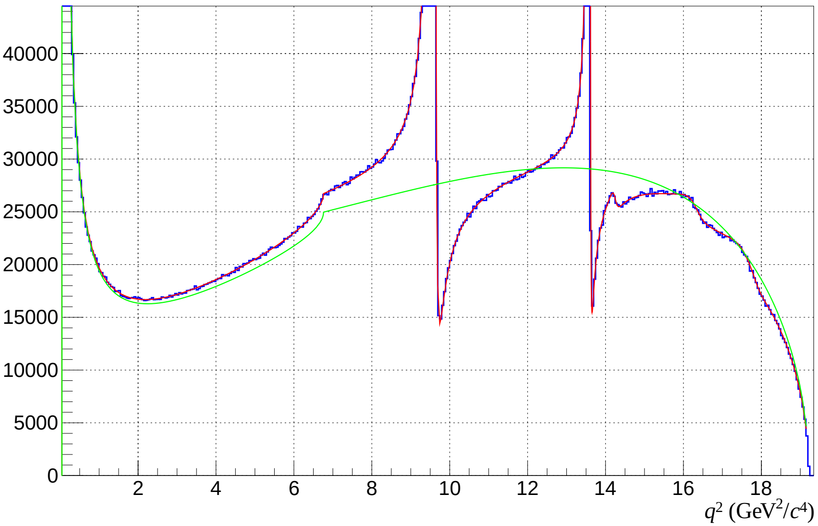
The old (naive) way:

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

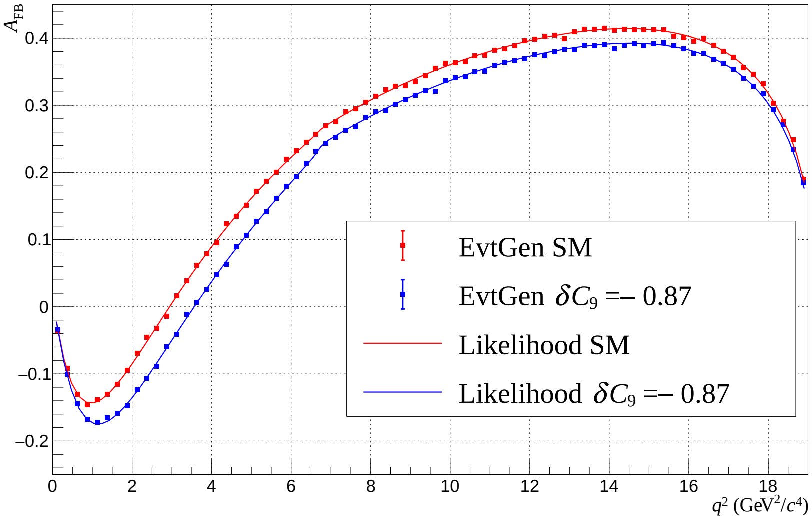
C_9 vs q^2 with $c\bar{c}$ resonances



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

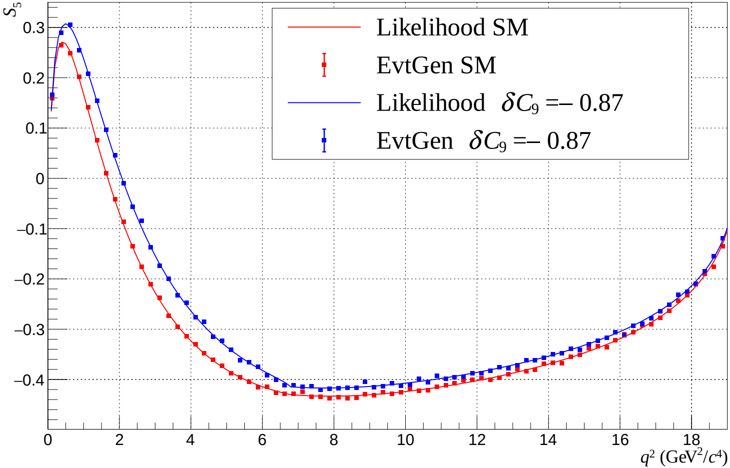


Angular observables



Here, $\delta C_9 = -0.87 \pm 0.18$ is taken from "New Physics in Rare B Decays after Moriond 2021" by Altmannshofer and Stangl. Note the shifts in S_5 and A_{FB} for this δC_9^{NP}.

Angular observables



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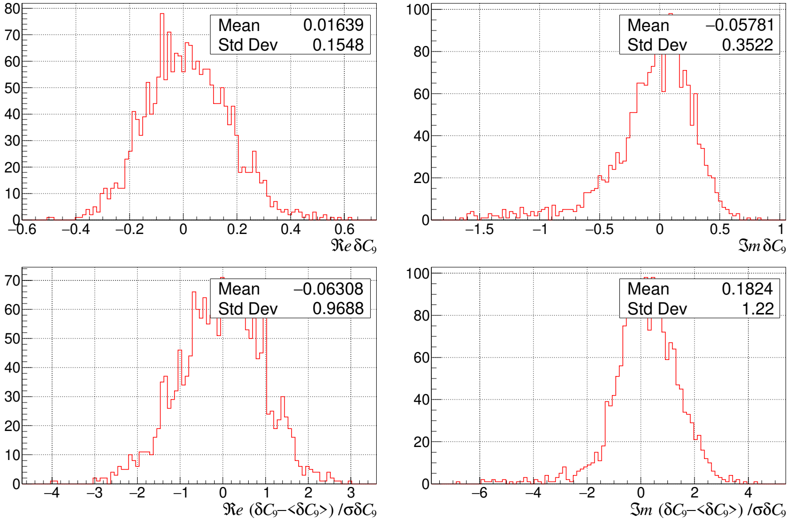
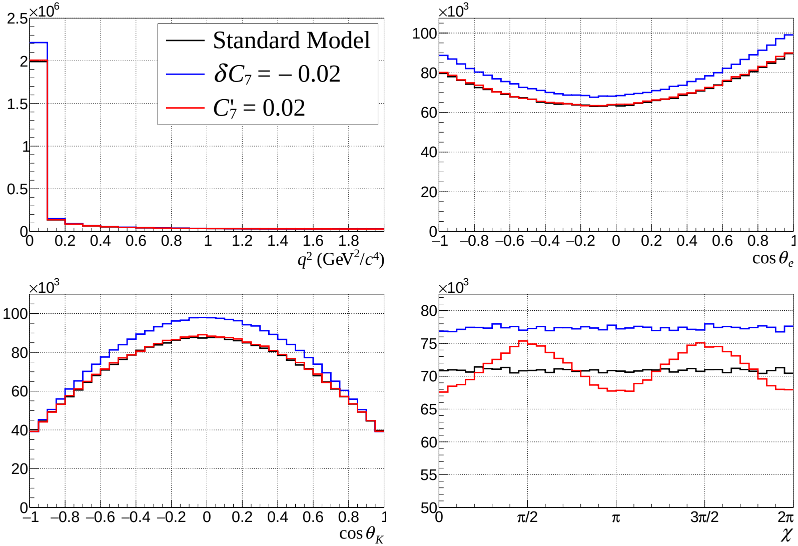
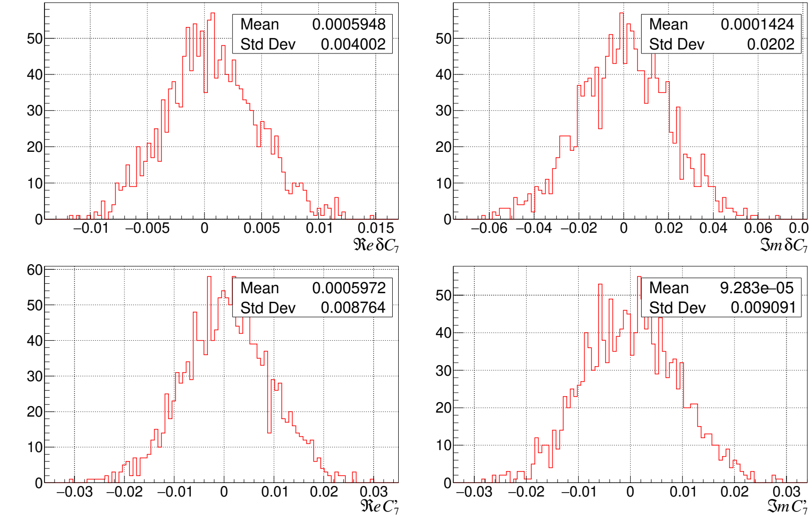


Based on the di-mion mode σ is about 3 and 7 % of $|C_9^{SM}|$ for the real and imaginary parts.

Effect of δC_7 and C_7' in $\bar{B} \to \bar{K}^* e^+ e^-$

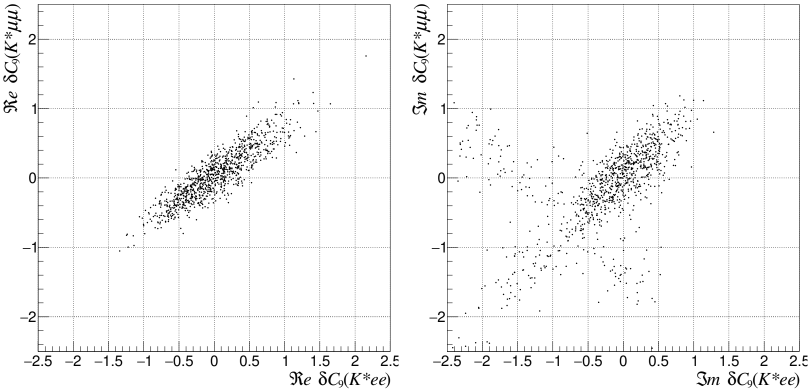


Sensitivity to δC_7 and C_7' with likelihood fit and 50/ab



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'.

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.

Conclusions

- The generator enables evaluation of the experimental sensitivity to various New Physics models in $B \to K^* \ell^+ \ell^-$ decays.
- 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].
- More sensitivity tests with various combinations of the Wilson coefficients.
- Integrate the generator into the official `EvtGen` codebase.