

New physics MC generator for $B \rightarrow K^* \ell^+ \ell^-$ decays

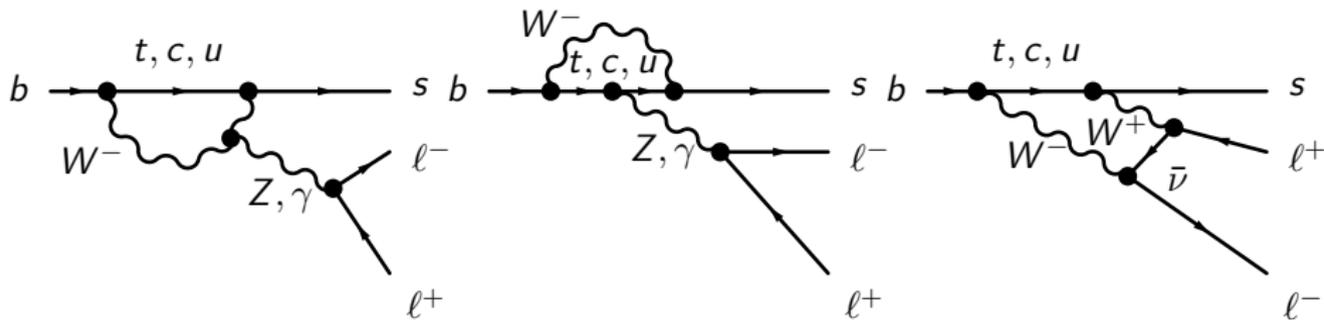
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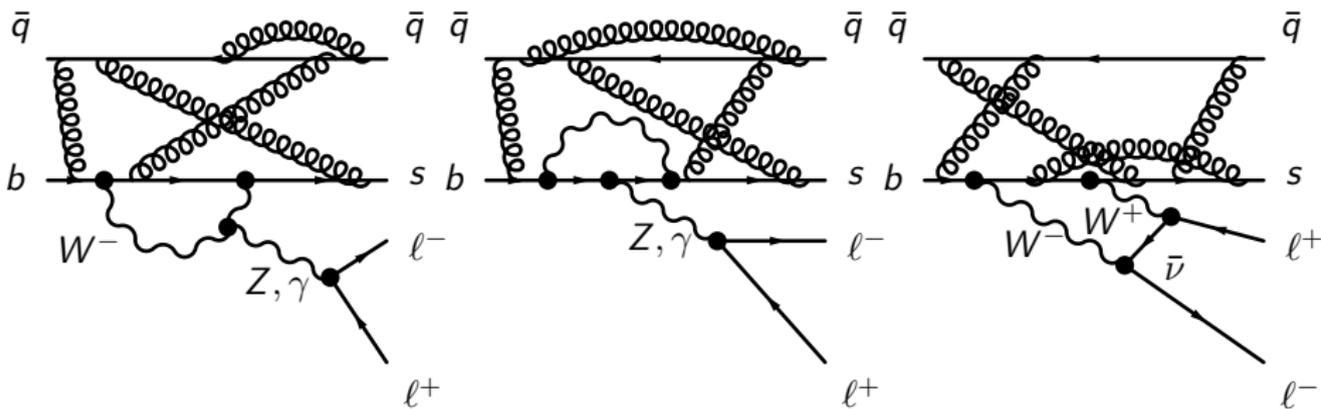
- The semileptonic decay $B \rightarrow K^* \ell^+ \ell^-$ is of particular relevance in new physics searches since it involves flavor-changing neutral current transitions (FCNC) and is forbidden in the standard model at tree level. Its angular distributions gives access to observables that are sensitive to NP.
- EvtGen is a particle generator framework which provides convenient tools to implement such complex decays and to test the sensitivity of the Belle II detector to various NP models with realistic detector efficiencies and background conditions.
- A $B \rightarrow K^* \ell^+ \ell^-$ decay generator with New Physics contributions which cover all possible dimension 6 operators has been implemented in EvtGen, based on the SM variant.
- EvtGen version 2 with this $B \rightarrow K^* \ell^+ \ell^-$ New Physics decay generator has been integrated into the Belle II software environment(BASF2).

SM lowest-order contributions



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At the lowest-order in the SM, the process $b \rightarrow s \ell \ell$ 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 with NP contributions

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 $B \rightarrow K^*(\rightarrow K\pi)\ell^+\ell^-$ as

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

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.

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

$$\begin{aligned} \langle \bar{K}^*(k) | \bar{s} \gamma_\mu (1 \mp \gamma_5) b | \bar{B}(p) \rangle = & \mp i \epsilon_\mu^* (m_B + m_{K^*}) A_1(q^2) \pm i (2p - q)_\mu (\epsilon^* \cdot q) \frac{A_2(q^2)}{m_B + m_{K^*}} \\ & \pm i q_\mu (\epsilon^* \cdot q) \frac{2m_{K^*}}{q^2} [A_3(q^2) - A_0(q^2)] + \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu} p^\rho k^\sigma \frac{2V(q^2)}{m_B + m_{K^*}}, \end{aligned} \quad (17)$$

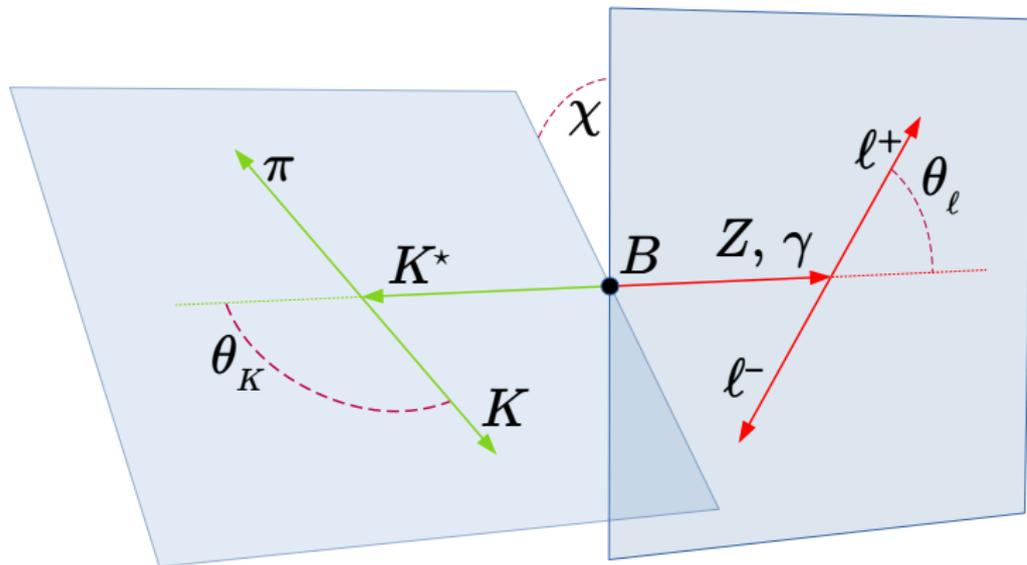
$$\text{with } A_3(q^2) = \frac{m_B + m_{K^*}}{2m_{K^*}} A_1(q^2) - \frac{m_B - m_{K^*}}{2m_{K^*}} A_2(q^2) \text{ and } A_0(0) = A_3(0); \quad (18)$$

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

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



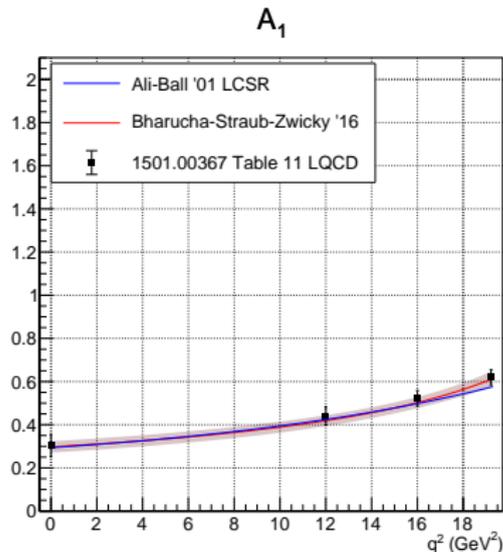
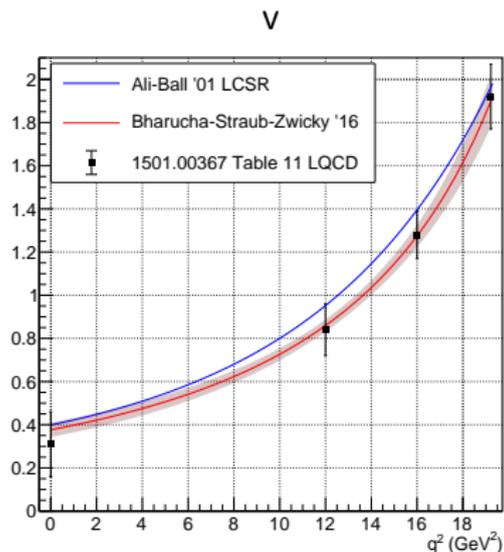
The kinematics of the decay are fully described by 4 parameters:

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

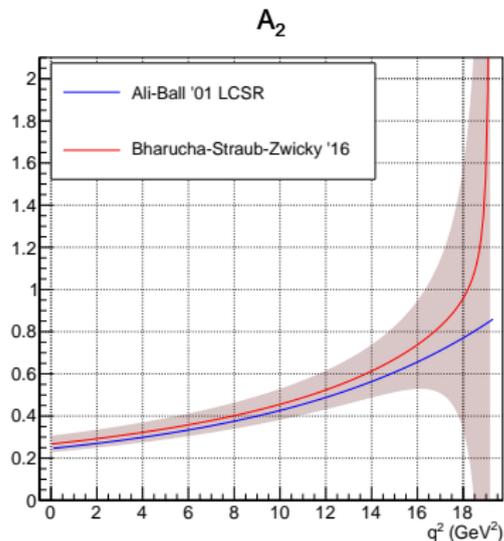
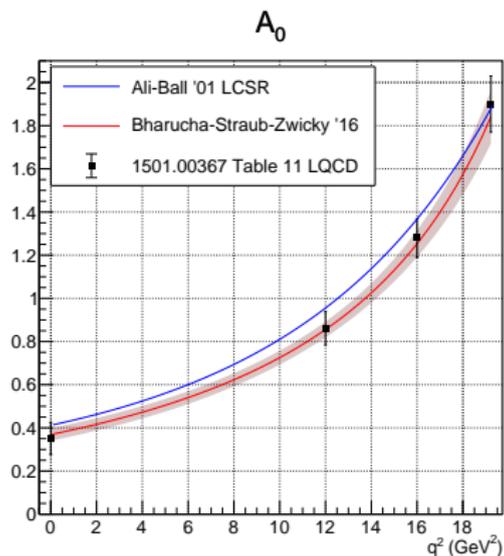
θ_ℓ and θ_K are defined with respect to the B momentum in the corresponding rest frames. q^2 is the invariant mass squared of the leptons.

Updated hadronic form factors

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

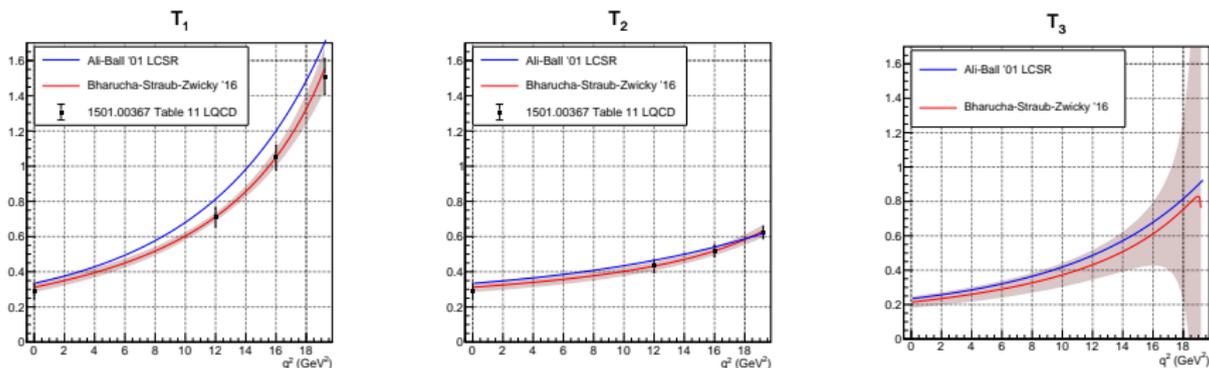


The old default form factors in EvtGen (blue line) still look good enough.



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:

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

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

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.

Implementation of the generator

To accommodate New Physics changes in the $B \rightarrow K^* \ell^+ \ell^-$ generator and expose them to the end user the following changes have been made:

- A new $b \rightarrow s \ell \ell$ vector amplitude was introduced: `EvtbTos11VectorAmpNP`.
- The ABSZ hadronic form factor parameterization for the process $b \rightarrow s \ell \ell$ was introduced: `EvtbTos11BSZ`. This is the most recent joined LCSR+LQCD calculation by Bharucha, Straub, and Zwicky [JHEP 08, 098 \(2016\), \[arXiv:1503.05534\]](#).
- A new decay model was introduced—BTOSLLNP—where the end user can set non-zero constant complex Wilson coefficients for right handed currents.
- Various performance improvements into the EvtGen codebase.

Example decay with non-zero C'_7 in c7_kstaree.dec

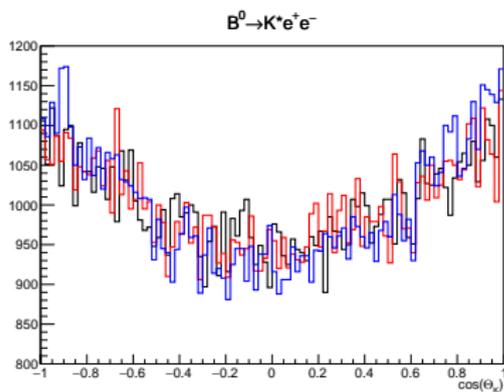
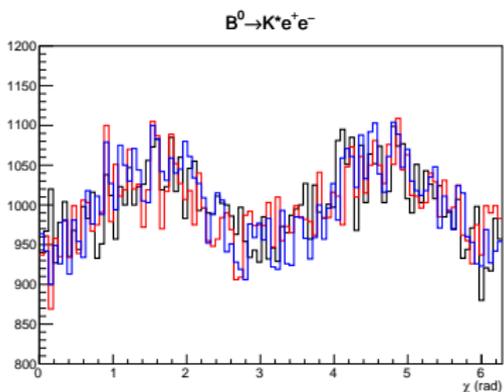
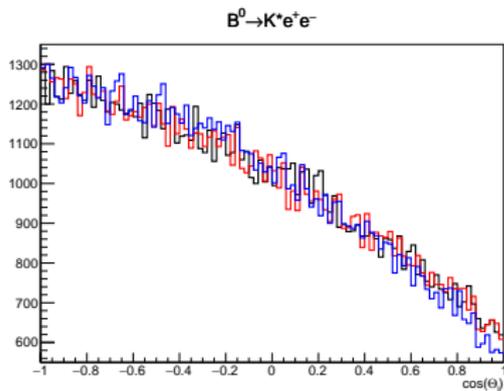
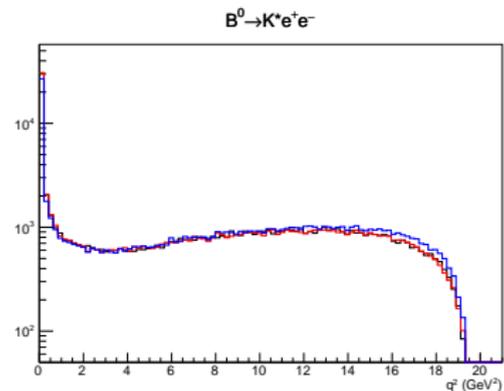
Decay anti-B0

```
# first argument is Cartesian(0) or polar(1) representation
# of NP coefficients which are three consecutive numbers
# {id, Re(C), Im(C)} or {coeff id, |C|, Arg(C)}
#
# id==0 delta C_7eff -- addition to NNLO SM value
# id==1 delta C_9eff -- addition to NNLO SM value
# id==2 delta C_10eff -- addition to NNLO SM value
# id==3 C'_7eff -- right handed polarization coefficient
# id==4 C'_9eff -- right handed polarization coefficient
# id==5 C'_10eff -- right handed polarization coefficient
# id==6 (C_S - C'_S) -- scalar right and left handed
# polarizations coefficient
# id==7 (C_P - C'_P) -- pseudo-scalar right and left handed
# polarizations coefficient

1.000 anti-K*0 e+ e- BTOSLLNP 1 3 0.39 1.5707963267;
# C'_7eff = 0.39*(cos(pi/2), sin(pi/2)) and all other
# coefficients are zero

Enddecay
```

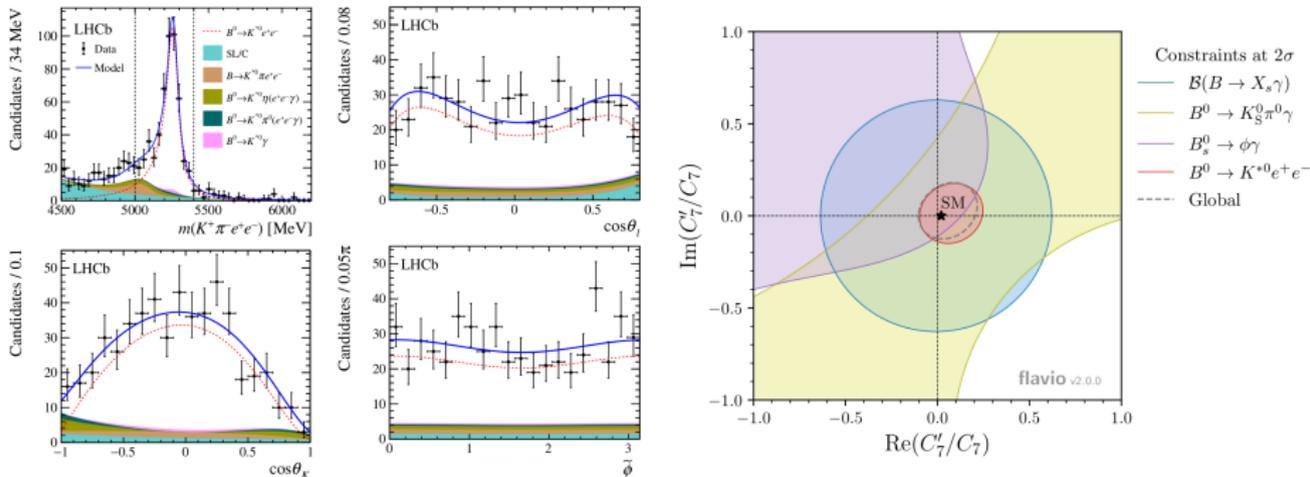
Distribution comparison (at generator level)



Default EvtGen BTOSLLBALL, **BTOSLLBALL with improved EvtGen**,
BTOSLLNP with all NP coefficients set to 0.

LHCb limit on C_7'

R. Aaij *et al.* [LHCb], "Strong constraints on the $b \rightarrow s\gamma$ photon polarisation from $B^0 \rightarrow K^{*0}e^+e^-$ decays," JHEP **12**, 081 (2020) [arXiv:2010.06011].

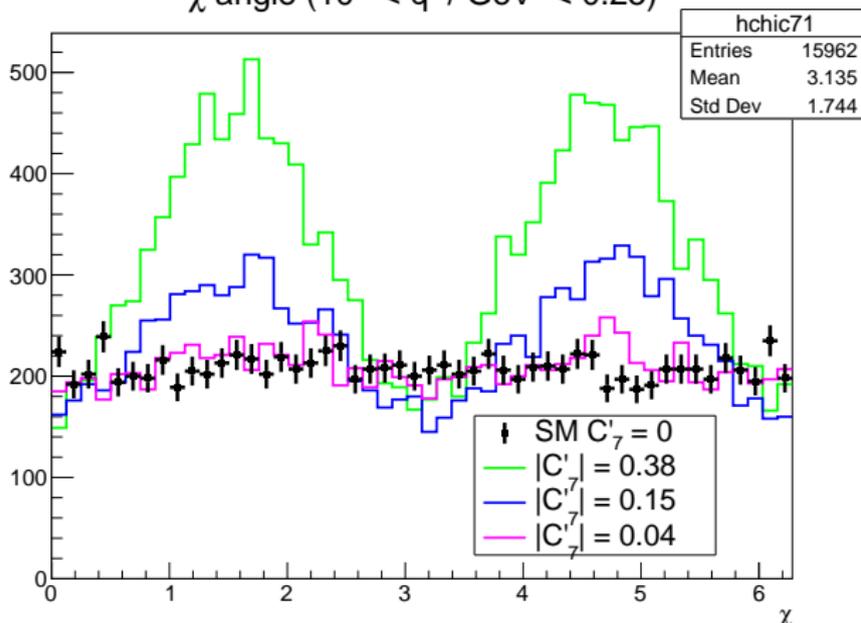


In the SM NNLO $|C_7| \approx 0.39$. Effective q^2 acceptance is $8 \times 10^{-4} < q^2/\text{GeV}^2 < 0.257$.

C_7' and χ angular distribution with Belle II data

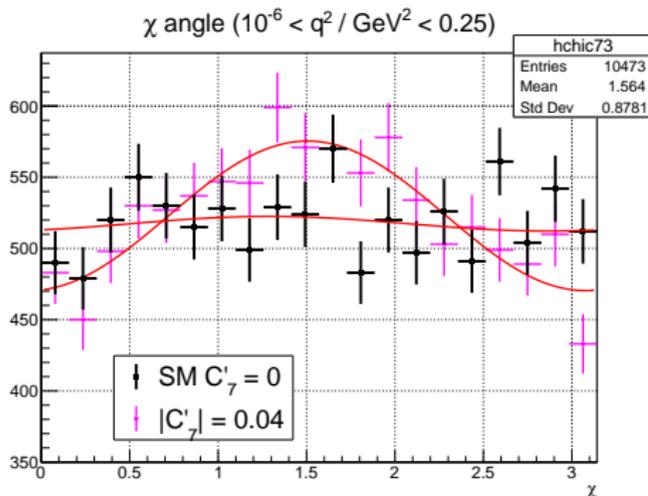
1 ab^{-1} collected at the $\Upsilon(4S)$ is equivalent to $1.086 \times 10^9 B\bar{B}$ pairs or $1.055 \times 10^9 B^0$ or \bar{B}^0 mesons and with $\mathcal{B}(B^0 \rightarrow K^* e^+ e^-) = (1.03_{-0.17}^{+0.19}) \times 10^{-6}$ from PDG about 1087 decays of both flavors are expected per $1/\text{ab}$. With $50/\text{ab}$ and assuming all particles are reconstructed in the magnetic spectrometer we might expect:

χ angle ($10^{-6} < q^2 / \text{GeV}^2 < 0.25$)



C_7' sensitivity with Belle II data

Assuming 69% reconstruction efficiency and histogram binning as in the LHCb paper.



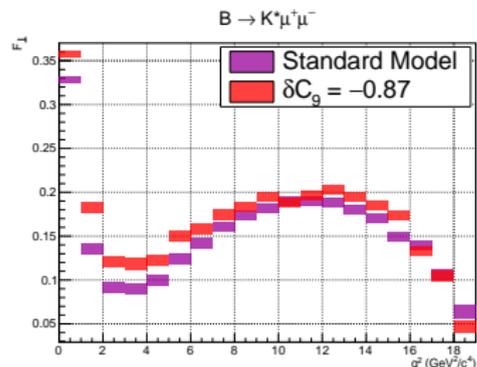
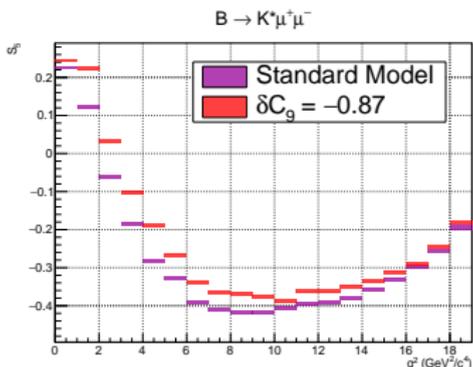
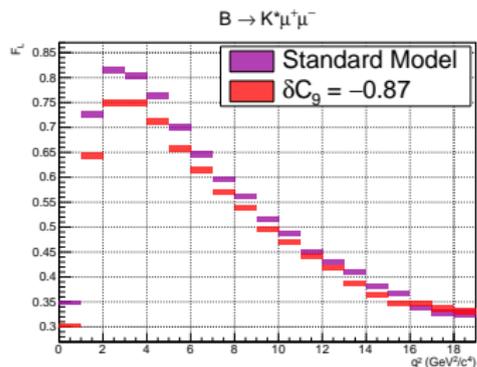
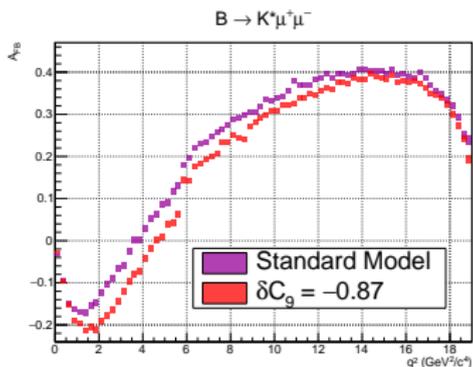
Fitted by $A \cos^2(\chi + \varphi) + B$

	$C_7' = 0$	$C_7' = 0.04$
A	10.3 ± 14.4	105 ± 14.4
$A/\delta A$	0.71	7.28

With 50/ab of data the $|C_7'|$ coefficient might be constrained better than $0.05 \times |C_7|$. Backgrounds and experimental selection efficiencies may reduce the sensitivity.

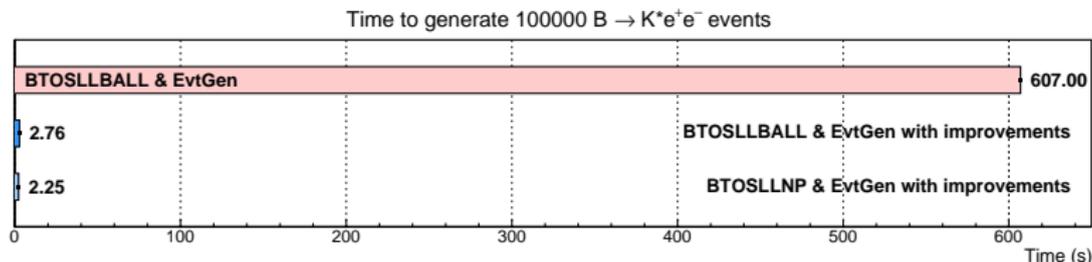
Another way to constrain $|C_7'|$ might be $d\Gamma/dq^2$ dependence – non-zero $|C_7'|$ should enhance the region near $q^2 = 0$.

Other possible observables (at generator level)



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} .

Performance improvements



A number of performance improvements have been made to EvtGen:

- The phase space generation procedure has been reviewed and improved.
- Tensor operations have been reviewed and improved.
- Importance sampling for $B \rightarrow K^* \ell^+ \ell^-$ decays or three body decay with a pole has been checked and a correct treatment of the pole has been implemented.
- The maximal amplitude search has been modified for $B \rightarrow K^* \ell^+ \ell^-$ decays.

- The generator enables evaluation of the experimental sensitivity to various New Physics models in $B \rightarrow K^* \ell^+ \ell^-$ decays.
- The generator is being tested within the Belle II environment.
- Reconstruction efficiencies of the Belle II magnetic spectrometer should suffice to probe a q^2 region unreachable at LHCb for $B \rightarrow K^* e^+ e^-$ decays.
- Next:
 - Introduce J/ψ and Ψ' vector resonances to estimate how they affect observables.
 - Integrate performance improvements into the official EvtGen codebase.