$B \to K^*\ell^+\ell^-$ generator with new physics contributions

Alexei Sibidanov

University of Hawaii

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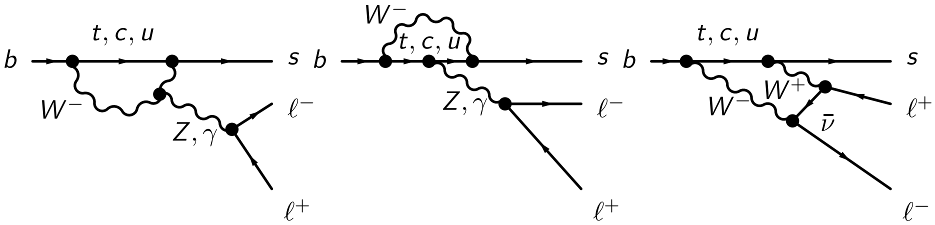
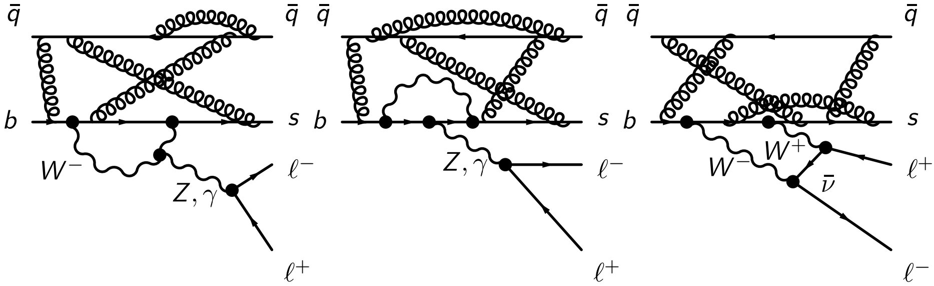
Introduction

- The semileptonic $B \to K^* \ell^+ \ell^-$ decay is of particular relevance in new physics searches since it involves flavour-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 decay and to test sensitivity of the Belle II detector to various NP models with realistic detector efficiencies and background conditions.
- The $B \to K^* \ell^+ \ell^-$ decay generator with New Physics contributions has been implemented in `EvtGen` based on the SM variant.
- `EvtGen` version 2 with $B \to K^* \ell^+ \ell^-$ New Physics decay generator has been integrated into Belle II software environment(BASF2)



The lowest-order SM $b \to s\ell\ell$ process is an interference of the γ/Z penguins and the W^-W^+ box diagrams.

SM lowest-order contributions



The lowest-order SM $b \to s\ell\ell$ process is an interference of the γ/Z penguins and the W^-W^+ box diagrams.

In addition this complex at the quark level process is spoiled by the QCD interactions and thus requires evaluation of the hadronic form factors.

The matrix element with NP contributions

The matrix element by Rusa Mandal & Rahul Sinha.

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

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

C_7', C_9', C_{10}', C_S, C_P, C_S', and C_P' coefficients correspond to NP contributions. Scalar and pseudoscalar contributions are vanished in the SM limit.

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

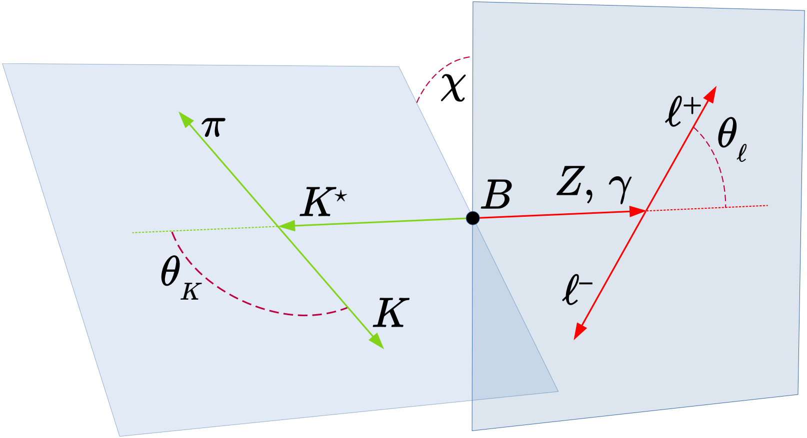
$$\text{with } A_3(q^2) = \frac{m_B+m_{K^*}}{2m_{K^*}}A_1(q^2) - \frac{m_B-m_{K^*}}{2m_{K^*}}A_2(q^2) \text{ and } A_0(0)=A_3(0); \quad (18)$$

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

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



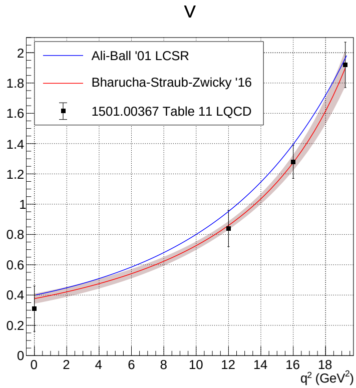
Kinematic of the decay is fully described by 4 parameters:

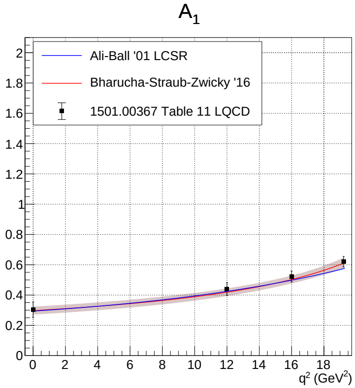
$$\frac{\Gamma(B \to K\pi\ell^+\ell^-)}{\mathrm{d}q^2\ \mathrm{d}\cos\theta_\ell\ \mathrm{d}\cos\theta_K\ \mathrm{d}\chi}$$

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

Updated hadronic form factors

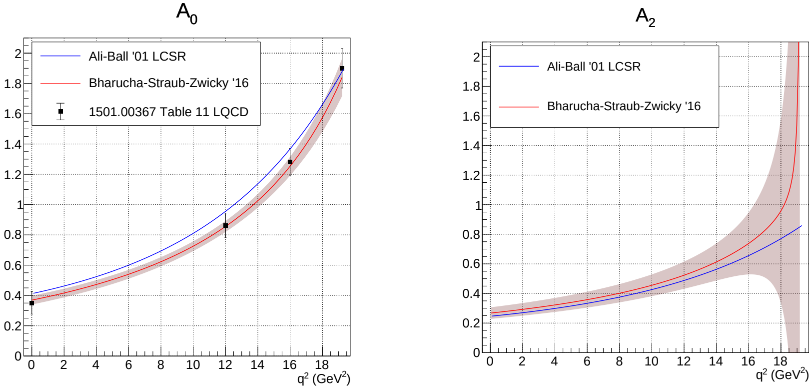
A. Bharucha, D. M. Straub and R. Zwicky, JHEP 1608, 098 (2016) [arXiv:1503.05534]. This parametrization is also know as the ABSZ form factor parameterization. Joined fit to the LCSR and LQCD calculations.





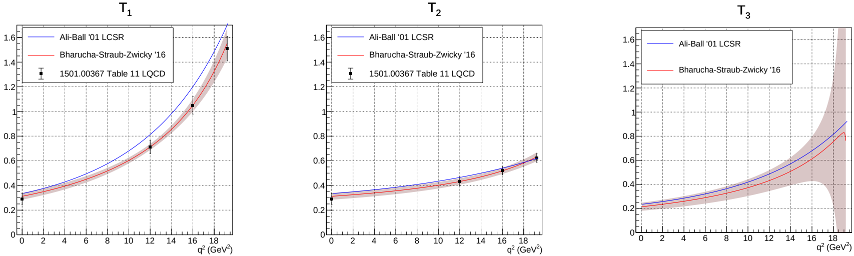
The old default form factors in EvtGen (blue line) still look good enough.

Form factors



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 A_2 and T_3 form factor are 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.

Implementation of the generator

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

- A new $b \to s\ell\ell$ vector amplitude was introduced: `EvtbTosllVectorAmpNP`.
- The ABSZ hadonic form factor parameterization for $b \to s\ell\ell$ process was introduced: `EvtbTosllBSZ`. This the 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 hand currents.
- Various performance improvements into the EvtGen codebase as well as bugfixes.

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 hand polarization coefficient
# id==4 C'_9eff -- right hand polarization coefficient
# id==5 C'_10eff -- right hand polarization coefficient
# id==6 (C_S - C'_S) -- scalar right and left hand
#    polarizations coefficient
# id==7 (C_P - C'_P) -- pseudo-scalar right and left hand
#    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
```

Initial setup

- Login to KEKCC
- Make a directory for the session: `mkdir kstarll`
- Go inside the directory: `cd kstarll`
- Copy content of the session:
  cp /home/belle/sibid/public/BelleIISummerWorkshop20210714/* .
- Setup Belle II environment with New Physics addition to EvtGen:
  source kstarll_setup

Standalone generator

- Source code: `kstarll_test.cc`
- Compilation – simply type: `make`
- Produce 100000 decays of $\bar{B}^0 \to \bar{K}^* e^+ e^-$ according to SM:
  `./run_kstarll -n 100000 -b anti-B0 -l e -p sm`
- Produce 100000 decays of $B^0 \to K^* e^+ e^-$ according to SM:
  `./run_kstarll -n 100000 -b B0 -l e -p sm`
- Then two files appear in the director:
  `sm_anti-B0_to_kstar_ee.root` and `sm_B0_to_kstar_ee.root`
- Review ntuple content in ROOT:

```
root -l sm_anti-B0_to_kstar_ee.root
ntp->Print();
ntp->Draw("q2");
.q
```

- Draw A_{FB}:
  `root -l -b -q 'draw_AFB.C("sm","e",1)'`
  file `AFB_e.pdf` appears in the directory.

Standalone generator and New Physics

- Exemplary decay files: `{sm,c7,all}_kstar{ee,mumu,tautau}.dec`
- Prefix `"sm"` stands for Standar Model
- Prefix `"c7"` stands for non zero C_7'
- Prefix `"all"` stands that all available in the generator New Physics coefficients are non zero.
- Produce 100000 decays of $\bar{B}^0 \to \bar{K}^* \mu^+ \mu^-$ with non zero C_7':
  `./run_kstarll -n 100000 -b anti-B0 -l mu -p c7`
- Produce 100000 decays of $B^0 \to K^* \tau^+ \tau^-$ with all non zero New Physics coefficients:
  `./run_kstarll -n 100000 -b B0 -l tau -p all`

Full simulation with New Physics

- To produce 10 events of $\Upsilon(4S) \to B^0 \bar{B}^0$ where one B decays generically and the other as $B \to K^* e^+ e^-$ according to SM type: `basf2 run_sim_kstarll.py`
- Exemplary decay file for this steering script: `Upsilon4S_to_Bgen_Bkstaree.dec`
- The script output: `mdst_kstarll.root`