EvtGen model for $B \to D^* \ell \nu$ with New Physics (from a theorists' perspective)

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Open LHCb Workshop on semileptonic exclusive $b \to c$ decays

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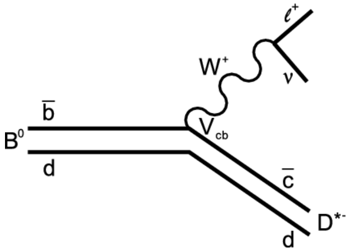
Exclusive semileptonic $b \to c\ell\nu$

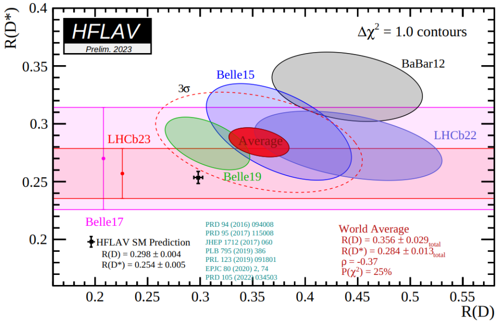
1. Semileptonic decays are theoretically clean : Leptonic current is decoupled from the hadronic current.
2. Here, we focus on $B \to D^*\ell\nu$ because :
   - Useful in the extraction of $|V_{cb}|$.
   - Testing CKM unitarity.
   - Sensitive probes of New Physics.
   - Unlike the $B \to K^*\ell\ell$ decay, this one does not suffer from pollution by charm resonances.
   - Test Lepton Flavour Universality of the SM.



Clean Observables

Lepton-flavour violating observables :

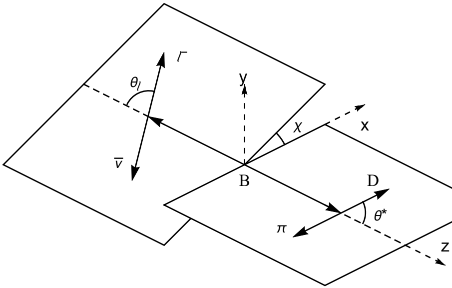
$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{(*)}\ell\bar{\nu}_\ell)} \text{ (with } \ell = e \text{ or } \mu)$$



Obs	SM	WA
$R_{D^*}^{\tau/\ell}$	0.254 ± 0.005 *HFLAV 2023*	0.284 ± 0.013 *HFLAV 2023*
$R_{D}^{\tau/\ell}$	0.298 ± 0.004 *HFLAV 2023*	0.356 ± 0.029 *HFLAV 2023*
$R_{D^*}^{\mu/e}$	~ 1.0	$1.04 \pm 0.05 \pm 0.01$ *Belle 2017*

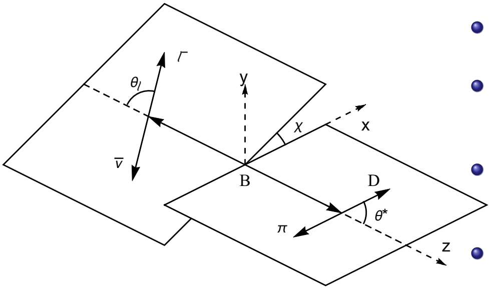
Possible new physics in tau, with electron and muon modes in good agreement with SM.

Going beyond the ratios : Angular analyses



- q^2 : the lepton-neutrino invariant mass squared.
- θ_ℓ : the angle between the direction of the lepton & the direction opposite the D^* meson in the virtual W rest frame.
- θ_{D^*} : the angle between the direction of the D^0 meson & the direction of the D^* meson in the D^* rest frame.
- χ : azimuthal angle between the two decay planes.

Going beyond the ratios : Angular analyses



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$$\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = \frac{d\Gamma}{dq^2}\left(\frac{1}{2} + A_{FB} \cos\theta_\ell + \frac{1-3\,\tilde{F}_L^\ell}{4}\,\frac{3\cos^2\theta_\ell - 1}{2}\right)$$

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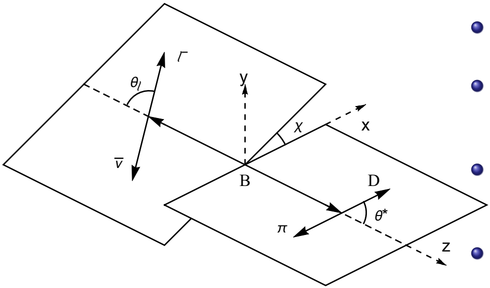

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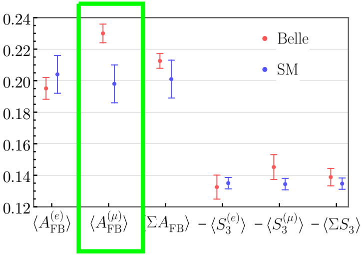
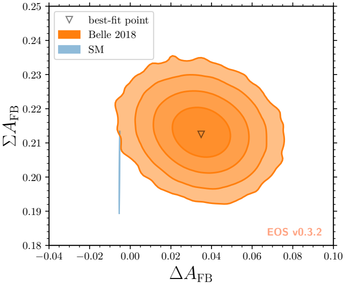
$$\frac{d^2\Gamma}{dq^2\,d\chi} = \frac{1}{2\pi}\frac{d\Gamma}{dq^2}\left(1 + S_3\cos 2\chi + S_9\sin 2\chi\right)$$

Belle provides for the first time, binned CP-averaged measurements of the four single-differential distribution for electron and muon (711 fb^{-1})



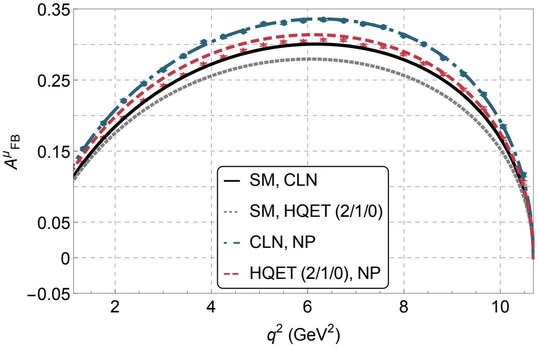


C. Bobeth et al, 2104.02094

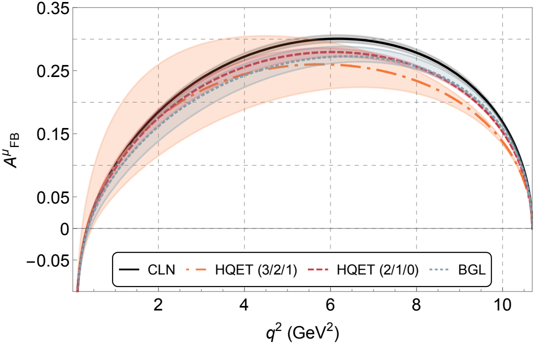
- Bobeth et. al studies some of the angular observables using the Belle data.
  Phys. Rev. D 100 (2019), 052007
  arxiv : 2104.02094
- Reports a $> 2\sigma$ anomaly in $\langle A_{FB}^{\mu}\rangle$.
- And, $\sim 4\sigma$ anomaly in $\Delta A_{FB} = A_{FB}^{\mu} - A_{FB}^{e}$.
- $\langle A_{FB}^{\mu}\rangle^{SM} = 0.198 \pm 0.012$,
  $\langle A_{FB}^{e}\rangle^{SM} = 0.204 \pm 0.012$
- $\langle A_{FB}^{\mu}\rangle^{fit} = 0.2300 \pm 0.0059$,
  $\langle A_{FB}^{e}\rangle^{fit} = 0.1951 \pm 0.0069$,
  $\langle \Delta A_{FB}\rangle^{fit} = +0.0349 \pm 0.0089$

Are these angular observables really clean?
Prospects of angular analyses: See talks by F. Bernlochner, E. Kou, L. Grillo at this workshop

A closer look at A_{FB}



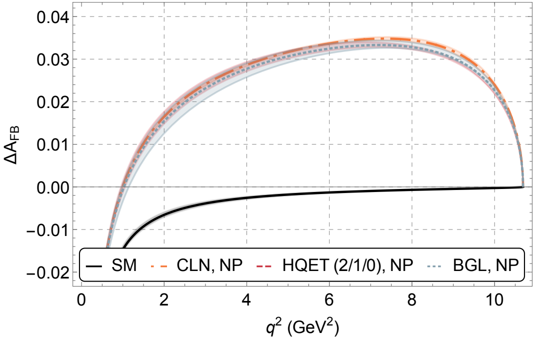
New Physics or Systematics?



- Difficult to disentangle NP from SM due to heavy dependence on form factors.

Δ Angular Observables

$$\Delta X = X^{\mu} - X^{e}$$



- Consider NP only in muon, while electron mode is well defined with SM.
- In case of SM, there is an almost exact cancellation of the hadronic uncertainties.
- $\Delta A_{FB}^{SM} \approx 0$
- Deviation from SM due to potential NP can be reliably extracted.

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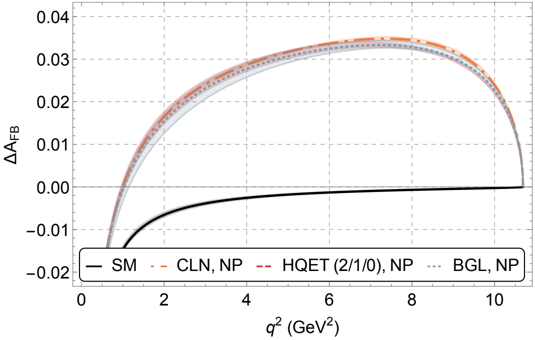

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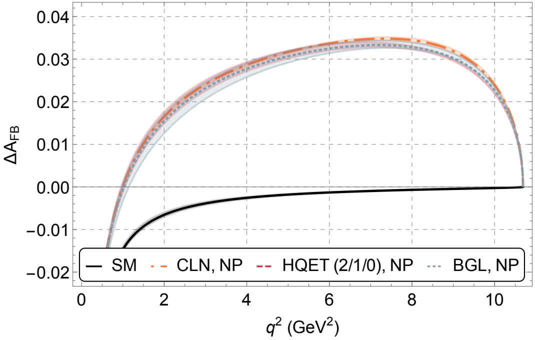

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What kinds of NP would provide potential signals in experiments?
New tools needed for NP studies!

MC for NP in $b \to c\ell\bar{\nu}$ decays

A new Monte-Carlo based on Evtgen:

https://github.com/qdcampagna/BTODSTARLNUNP_EVTGEN_Model

B.Bhattacharya, T.Browder, Q. Campagna, A. Datta, S. Dubey, A.Sibidanov, [2203.07189, 2206.11283]

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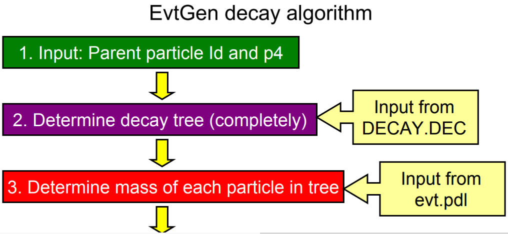
- **EvtGen** : is a MC event generator that simulates the decays of heavy flavour particles, primarily the B and D mesons.
  - Originally written by Anders Ryd and David Lange.
  - It has detailed models for semileptonic decays, CP-violating decays and produces correct results for the angular distributions in sequential decays, including all correlations.
  - At the moment only the SM is implemented.
  - For details of the algorithm, see the Tutorial

https://indico.cern.ch/event/411269/contributions/1867718/attachments/835829/1159322/tut-all.pdf



MC for NP in $b \to c\ell\bar{\nu}$ decays

$$\mathcal{H}_{eff} = \frac{G_F V_{cb}}{\sqrt{2}} \Big\{ (1+g_L)\,[\bar{c}\gamma_\mu(1-\gamma_5)b]\,\left[\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell\right]$$
$$+g_R\,[\bar{c}\gamma_\mu(1+\gamma_5)b]\,\left[\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell\right]$$
$$+g_S\,[\bar{c}b]\,\left[\bar{\ell}(1-\gamma_5)\nu_\ell\right]$$
$$+g_P\,[\bar{c}\gamma_5 b]\,\left[\bar{\ell}(1-\gamma_5)\nu_\ell\right]$$
$$+g_T\,\,[\bar{c}\sigma^{\mu\nu}(1-\gamma_5)b]\,\left[\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\right] \Big\} + h.c.$$

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Caveats :

1. Neutrinos are always left-handed.
2. The scalar matrix element $\langle D^*|\bar{c}b|\bar{B}\rangle = 0$
3. SM case : $g_L = g_R = g_P = g_T = 0$
4. Alternate convention :
   $C_{V_L} = 1+g_L\,, \quad C_{V_R} = g_R\,, \quad C_{S_L} = g_S-g_P\,, \quad C_{S_R} = g_S+g_P\,, \quad C_T = g_T$

BTODSTARLNUNP Model

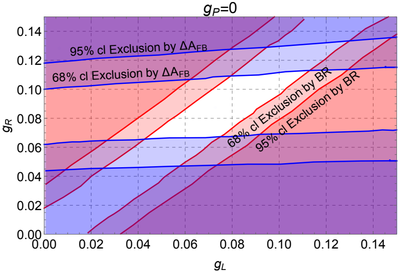
- We write a C++ model file `EvtSemiLeptonicVectorAmpNP.cpp` which is used to calculate the new physics decay amplitudes.
- A snippet from the decay file : `BB_dstarlnu_np.dec`

```
##need to turn off mixing to prevent B0 from becoming an anti-B0
Define dm_incohMix_B0 0.0

##Decay Upsilon(4S)
1 B0  anti-B0   VSS;
Enddecay

## Enter arguments for new physics parameters
## 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_VL -- left-handed vector coefficient change from SM
## id==1 C_VR -- right-handed vector coefficient
## id==2 C_SL -- left-handed scalar coefficient
## id==3 C_SR -- right-handed scalar coefficient
## id==4 C_T  -- tensor coefficient

Decay B0
## B0 -> D*- e+ nu_e is generated with the Standard Model only
1   D*-  e+  nu_e  BTODSTARLNUNP;
Enddecay

Decay anti-B0
## anti-B0 -> D*+ mu- anti-nu_mu is generated with the addition of New Physics
1   D*+   mu-   anti-nu_mu   BTODSTARLNUNP  0 0 0.06 0 1 0.075 0 2 0 -0.2 3 0 0.2;
Enddecay

End
```

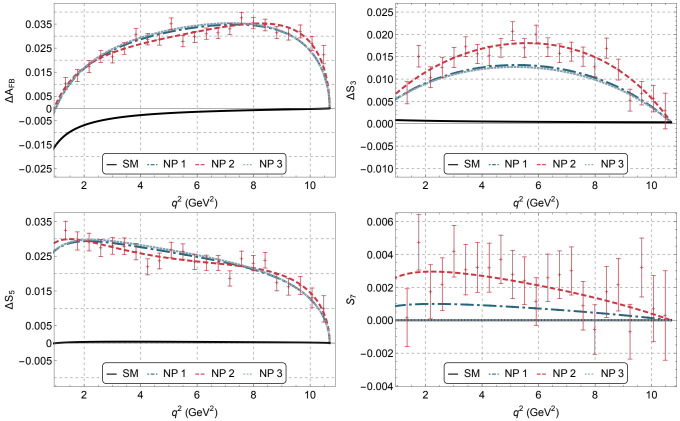
NP Analysis

- We pick out a few NP scenarios as listed below.
- The choice is motivated such that :
  - $R(\mu/e)$ is constrained to be within 3% of unity.
  - they are able to explain the"fitted" $\langle \Delta A_{FB} \rangle$: 0.0349 ± 0.0089.
  - they also satisfy constraints on other angular observables such as $\langle \Delta F_L \rangle^{exp} = -0.0065 \pm 0.0059$ and $\langle \Delta \tilde{F}_L \rangle^{exp} = -0.0107 \pm 0.0142$.

	g_L	g_R	g_P
Scenario 1:	0.06	0.075	0.2 i
Scenario 2:	0.08	0.090	0.6 i
Scenario 3:	0.07	0.075	0



Correlated Angular Asymmetries

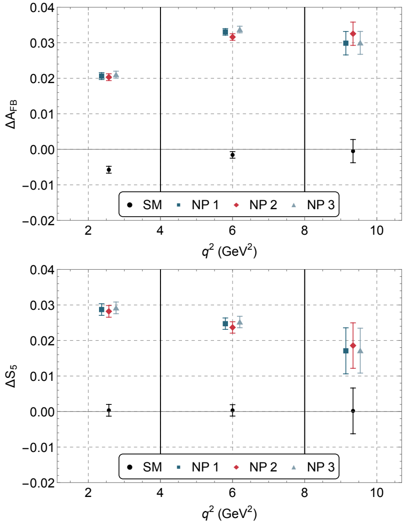


Plots with 10M events MC dataset at 50 ab^{-1} in q^2 bins of 0.4 GeV^2

- If there is NP, then one will observe signals in other angular asymmetries, not just in ΔA_{FB} .
- True CP violating observable S_7 in presence of complex new physics.

Belle II Sensitivities

- Coarse binning could be done to begin with.
- Here we use Belle fiducial cuts :
  - $p_T^{\mu,e} > 0.8$ GeV
  - $p_T^{\pi} > 0.1$ GeV
  - Angular acceptance of all final state particles : $-0.866 < \cos\theta < 0.956$
- Note that we use the same p_T cut for electron and muon since we did not include detector efficiencies for the leptons separately.



Stat uncertainties from MC simulation with $\int Ldt = 50ab^{-1}$

Summary & Outlook

- Distributions of angular asymmetries in $B \to D^* \ell \nu$ are interesting and important for new physics analyses.
- We expect angular asymmetries to provide tighter constraints on NP LFU couplings.
- New tools are needed to understand NP distributions and for experimentalists to devise their strategies.
- Δ-observables are ideally suited for such studies.
- Looking forward to more statistics from Belle II and LHCb.
- Untagged analysis at Belle II ($\int Ldt = 189.3 fb^{-1}$) : $\Delta A_{FB} = (-4 \pm 16_{stat} \pm 18_{sys}) \times 10^{-3}$ [Philipp Horak, this workshop]
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THANK YOU!

Backup

$$A_{FB}(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \, \frac{d^2\Gamma}{d\cos\theta_\ell dq^2},$$

$$S_3(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi/4} - \int_{\pi/4}^{\pi/2} - \int_{\pi/2}^{3\pi/4} + \int_{3\pi/4}^{\pi} + \int_{\pi}^{5\pi/4} - \int_{5\pi/4}^{3\pi/2} - \int_{3\pi/2}^{7\pi/4} + \int_{7\pi/4}^{2\pi}\right] d\chi \, \frac{d^2\Gamma}{dq^2 d\chi},$$

$$S_5(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi} - \int_{\pi}^{3\pi/2} + \int_{3\pi/2}^{2\pi}\right] d\chi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta^* \, \frac{d^3\Gamma}{dq^2 d\cos\theta^* d\chi},$$

$$S_7(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi} - \int_{\pi}^{2\pi}\right] d\chi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta^* \, \frac{d^3\Gamma}{dq^2 d\cos\theta^* d\chi}.$$