Probing BSM Physics in $B \to D^{*} \ell \nu$ using Monte Carlo Simulation

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arXiv:2203.07189

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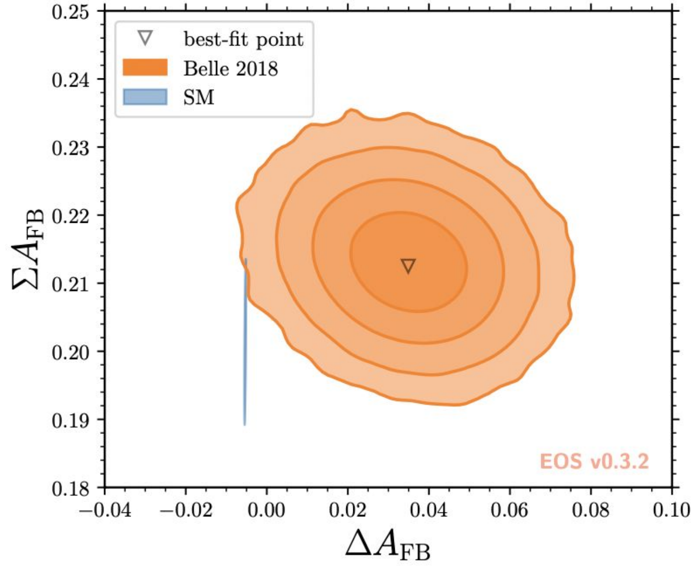
Introduction

- There are many experimental anomalies that point towards possible NP in $B \to D^* \ell \nu$
- One of these is an anomaly in A^μ_{FB} for $B \to D^* \ell \nu$, indicating possible NP in the μ mode (Bobeth et al., Eur.Phys.J.C 81 (2021) 11, 984)
- There are several experimental analyses that can be done with current and projected data sets to test possible NP scenarios

Observable	SM Prediction	Measurement (WA)
$R_{D^*}^{\tau/\ell}$	0.258 ± 0.005 [12]	$0.295 \pm 0.011 \pm 0.008$ [12]
$R_{D}^{\tau/\ell}$	0.299 ± 0.003 [12]	$0.340 \pm 0.027 \pm 0.013$ [12]
$R_{J/\psi}^{\tau/\mu}$	0.283 ± 0.048 [13]	$0.71 \pm 0.17 \pm 0.18$ [11]
$R_{D^*}^{\mu/e}$	~ 1.0	$1.04 \pm 0.05 \pm 0.01$ [14]



NP Monte Carlo

- Monte Carlo tools are useful for generating accurate theoretical predictions in realistic experimental environments
- In order to simulate NP scenarios, we have developed a new module for the EvtGen Monte Carlo tool
  - EvtGen previously has the SM module only for $B \to D^* \ell \nu$
- This module can be found at **github.com/qdcampagna/BTODSTARLNUNP_EVTGEN_Model**

Effective Hamiltonian

- Can parameterize NP in terms of right and left handed vectors, right and left handed scalars, and tensors
  - Recombine g_{sL} and g_{sR} to get a scalar (g_S) and pseudoscalar (g_P) contribution
- We assume that the electron mode is well described by the SM, so we only consider NP in the μ mode

$$\mathcal{M} = \frac{4G_F V_{cb}}{\sqrt{2}} \left\{ \langle D\pi | \bar{c}\gamma^\mu [(1+g_L)P_L + g_R P_R] b | \bar{B} \rangle (\bar{\mu}\gamma_\mu P_L \nu) + \langle D\pi | \bar{c}(g_{S_L} P_L + g_{S_R} P_R) b | \bar{B} \rangle (\bar{\mu} P_L \nu) + g_T \langle D\pi | \bar{c}\sigma^{\mu\nu} b | \bar{B} \rangle (\bar{\mu}\sigma_{\mu\nu} P_L \nu) \right\}$$

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Forward-Backward Asymmetry

- A_{FB} is the asymmetry of events with fermions produced in the forward region ($\cos\theta_\ell > 0$) vs those produced in the backward region ($\cos\theta_\ell < 0$)
- $\Delta A_{FB} = A^{\mu}_{FB} - A^{e}_{FB}$
- A_{FB} is heavily dependent on the choice of form factors, but ΔA_{FB} removes much of this dependence
- Note: the B factories have not measured A_{FB} so far, so we use our MC to to simulate NP scenarios that can produce a measurable deviation from the SM prediction

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

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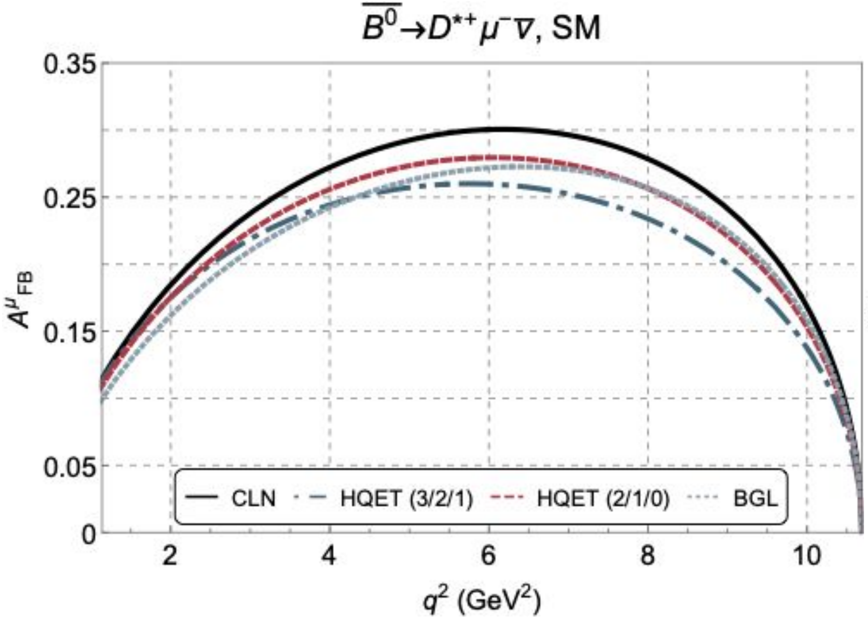
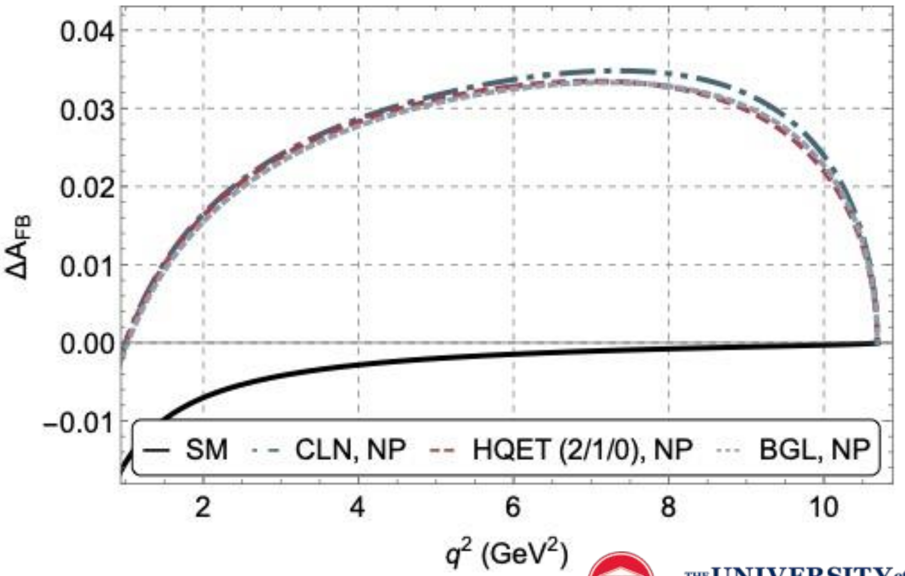
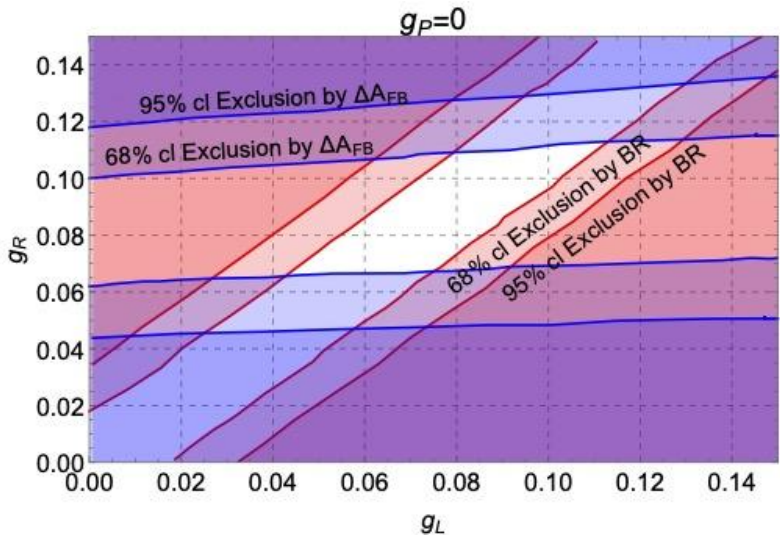
Asymmetries vs. Δ-Observables





Choosing NP Scenarios

- Used following constraints:
  - BR = B(B⟶D$^*\mu\nu$)/B(B⟶D$^*e\nu$)= 1 ± 3%
  - $\langle\Delta A_{FB}\rangle$= 0.0349 ± 0.0089 (from Bobeth et al. analysis of Belle 2019 data)



- Settled on 3 NP scenarios
  - NP1: g_L = 0.06, g_R = 0.075, g_P = 0.2i
  - NP2: g_L = 0.08, g_R = 0.090, g_P = 0.6i
  - NP3: g_L = 0.07, g_R = 0.075, g_P = 0

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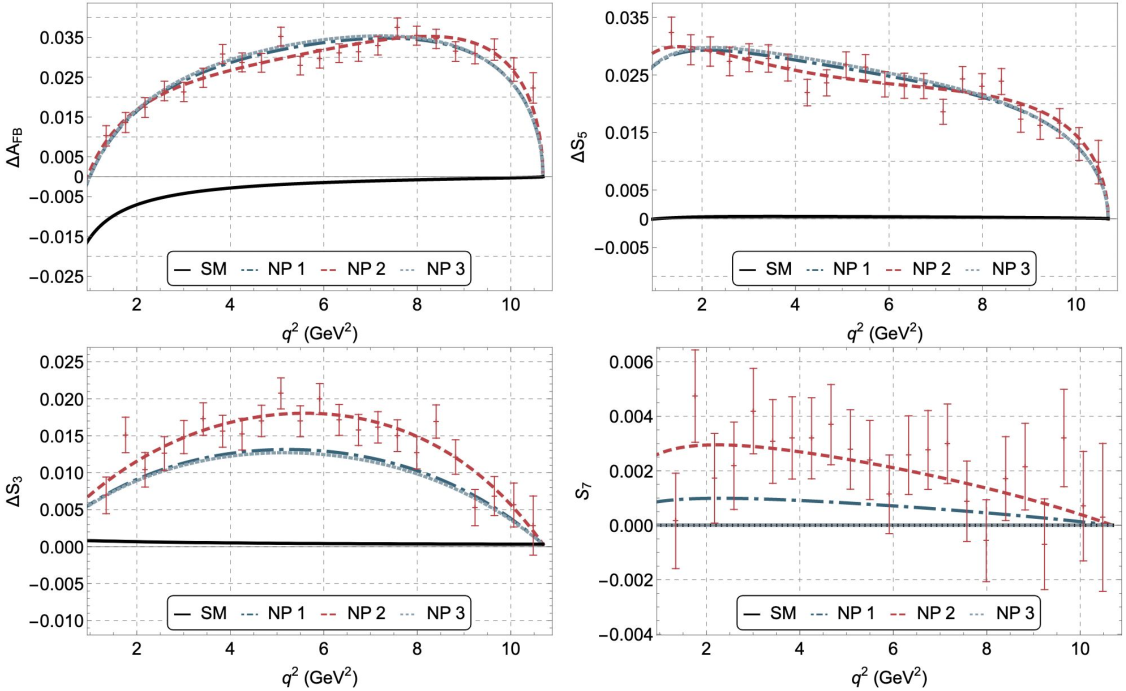
Correlated Asymmetries

- If there is truly NP, there will be signals in asymmetries other than ΔA_{FB}
- Will always see a ΔS_3 and ΔS_5 in the presence of NP
- S_7 is a true CP-violating asymmetry, and so will only appear in certain scenarios (ie imaginary g_P)
- MC shown for 50 ab^{-1} data set in q^2 bins of 0.4 GeV^2



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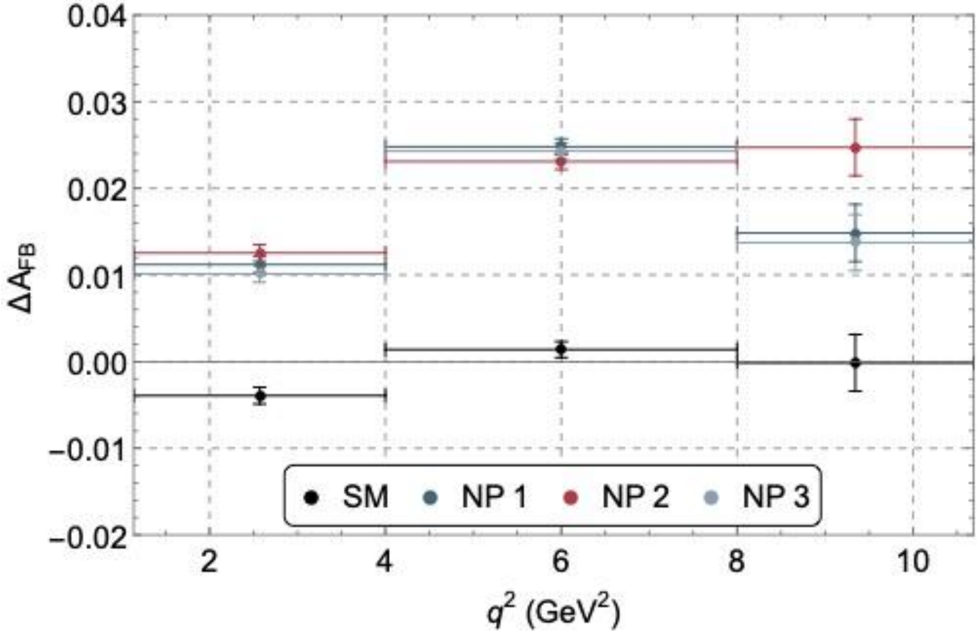
Belle II Sensitivities

- For current available Belle data (1 ab^{-1}) and projected Belle II data (50 ab^{-1}), we have simulated what can be expected if they decide to measure this anomaly
- We have used Belle fiducial cuts
  - Transverse momenta of the lepton (> 0.8 GeV) and the pion (> 0.1 GeV)
  - Angular acceptance of all final state particles ($-0.866 < \cos\theta < 0.956$)
- This plot shows the predicted ΔA_{FB} values in three discrete q^2 bins for the three NP scenarios we have focused on



Conclusions

- There are several indicators of possible NP in the $B \to D^* \ell \nu$ mode
- Δ-observables significantly reduce theoretical uncertainty due to form factors compared to straight asymmetries
- The presence of NP requires signals in several correlated observables
- A coarse q^2 bin analysis of these correlated observables can indicate NP with both current and projected data sets

Acknowledgements

- This work was supported by the **NSF Grant No PHY-191514**
- Thanks to Alakabha Datta, Lopamudra Mukherjee, Bhubanjyoti Bhattacharya, Thomas Browder, Alexei Sibidanov, and Shawn Dubey

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Integrated Values

- To date, ΔA_{FB} has been measured as an "integrated" quantity (using 1 q^2 bin that encompasses the entire desired range)
- The following values are measured from Monte Carlo simulation using Belle fiducial cuts on angular acceptance of final state particles, and the transverse momentum of the lepton and pion
  - Note: 1 ab^{-1} is the current available data from Belle, 50 ab^{-1} is the projected data with target Belle II luminosity

	$\langle \Delta A_{FB} \rangle$ (50ab^{-1})	$\langle \Delta A_{FB} \rangle$ (1ab^{-1})	$\langle \Delta S_5 \rangle$ (50ab^{-1})	$\langle \Delta S_5 \rangle$ (1ab^{-1})
NP 1:	0.019 ± 0.001	0.023 ± 0.005	0.019 ± 0.001	0.019 ± 0.006
NP 2:	0.018 ± 0.001	0.022 ± 0.007	0.016 ± 0.001	0.016 ± 0.006
NP 3:	0.017 ± 0.001	0.022 ± 0.007	0.019 ± 0.001	0.019 ± 0.006

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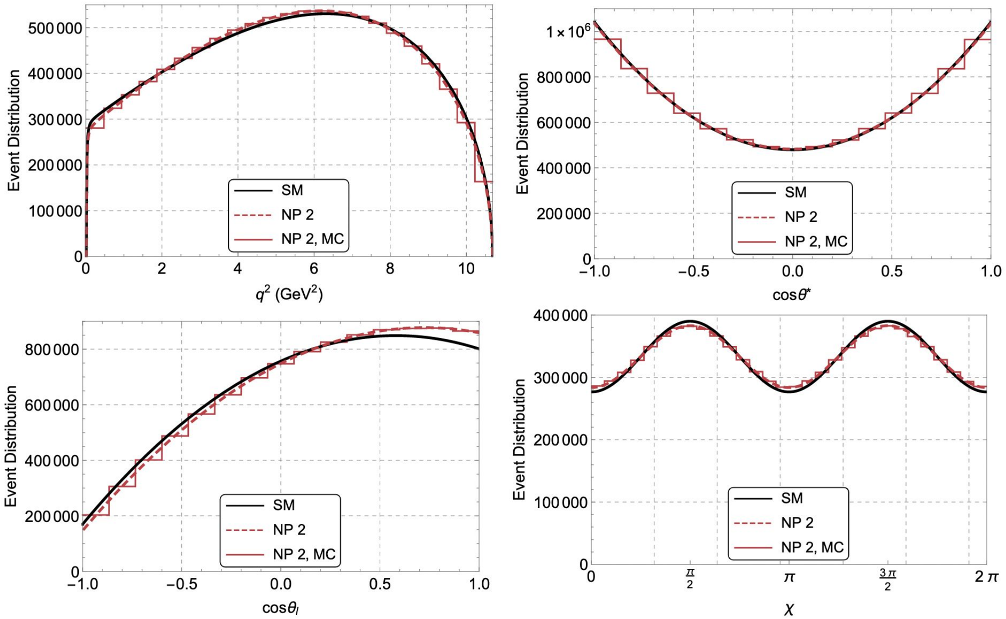
Kinematic Distributions



Observables

Observable	Angular Function	NP Dependence	m_ℓ suppression order
A_{FB}	$\cos\theta_\ell$	$\text{Re}\,[g_T g_P^*]$ $\text{Re}\,[(1+g_L-g_R)(1+g_L+g_R)^*]$	$\mathcal{O}(1)$
		$\text{Re}\,[(1+g_L-g_R)g_P^*]$ $\text{Re}\,[g_T(1+g_L-g_R)^*]$ $\text{Re}\,[g_T(1+g_L+g_R)^*]$	$\mathcal{O}(m_\ell/\sqrt{q^2})$
		$\|1+g_L-g_R\|^2$ $\|g_T\|^2$	$\mathcal{O}(m_\ell^2/q^2)$
S_3	$\sin^2\theta^*\sin^2\theta_\ell\cos 2\chi$	$\|1+g_L+g_R\|^2$ $\|1+g_L-g_R\|^2$ $\|g_T\|^2$	$\mathcal{O}(1),\ \mathcal{O}(m_\ell^2/q^2)$
S_5	$\sin 2\theta^*\sin\theta_\ell\cos\chi$	$\text{Re}\,[g_T g_P^*]$	$\mathcal{O}(1)$
		$\|1+g_L-g_R\|^2$	$\mathcal{O}(1),\ \mathcal{O}(m_\ell^2/q^2)$
		$\text{Re}\,[(1+g_L-g_R)g_P^*]$ $\text{Re}\,[g_T(1+g_L-g_R)^*]$ $\text{Re}\,[g_T(1+g_L+g_R)^*]$	$\mathcal{O}(m_\ell/\sqrt{q^2})$
		$\|g_T\|^2$	$\mathcal{O}(m_\ell^2/q^2)$
S_7	$\sin 2\theta^*\sin\theta_\ell\sin\chi$	$\text{Im}\,[g_P g_T^*]$	$\mathcal{O}(1)$
		$\text{Im}\,[(1+g_L+g_R)g_P^*]$ $\text{Im}\,[(1+g_L-g_R)g_T^*]$	$\mathcal{O}(m_\ell/\sqrt{q^2})$
		$\text{Im}\,[(1+g_L-g_R)(1+g_L+g_R)^*]$	$\mathcal{O}(m_\ell^2/q^2)$

Asymmetry Definitions

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

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

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

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

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