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

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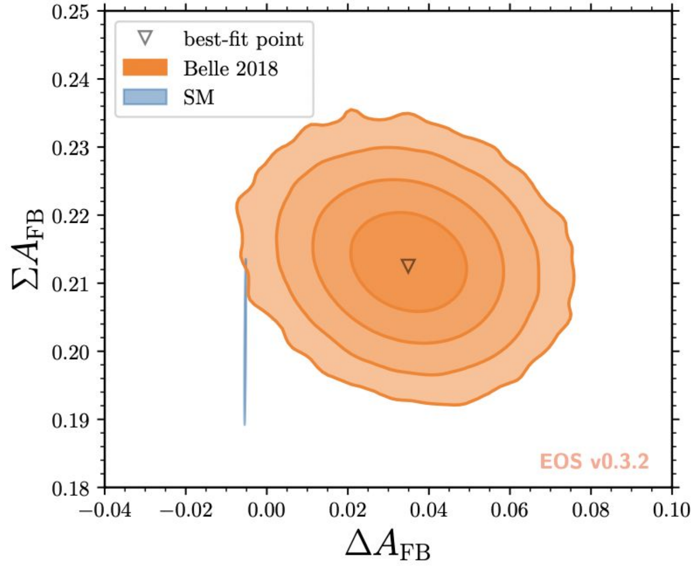
Introduction

- 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]



Effective Field Theory

- Write down all possible 6-D operators on b quark mass scale
- 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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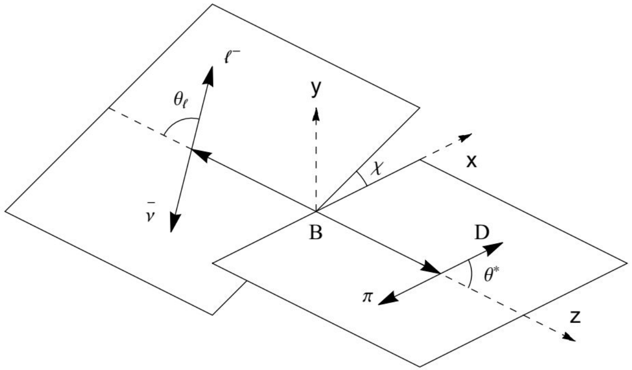
Differential Decay Distributions

- Ranges of kinematic variables:
  - $m_\ell^2 \leq q^2 \leq (m_B - m_{D^*})^2$
  - $0 \leq \theta_{D^*,\ell} \leq \pi$
  - $0 \leq \chi \leq 2\pi$
- Can perform asymmetric integrals over one or more angles to construct observables



Forward-Backward Asymmetry

- A_{FB} is the asymmetry of events with leptons 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
- 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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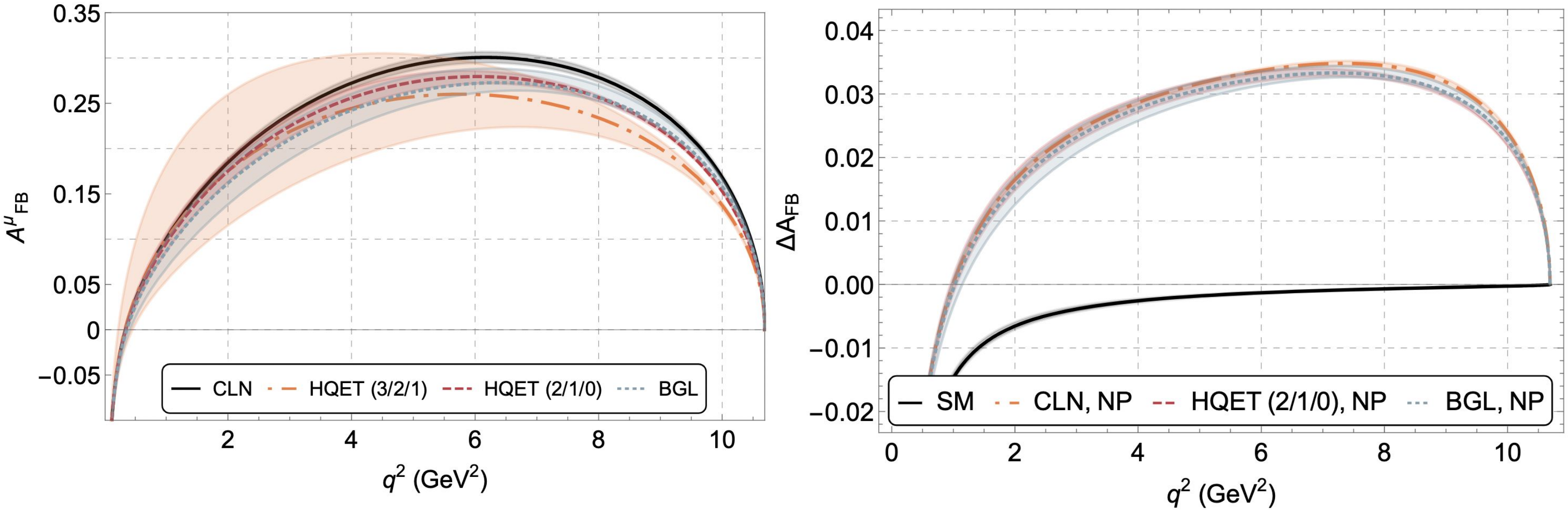
Asymmetries vs. Δ-Observables



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NP Monte Carlo

- 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**

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```
## 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
```

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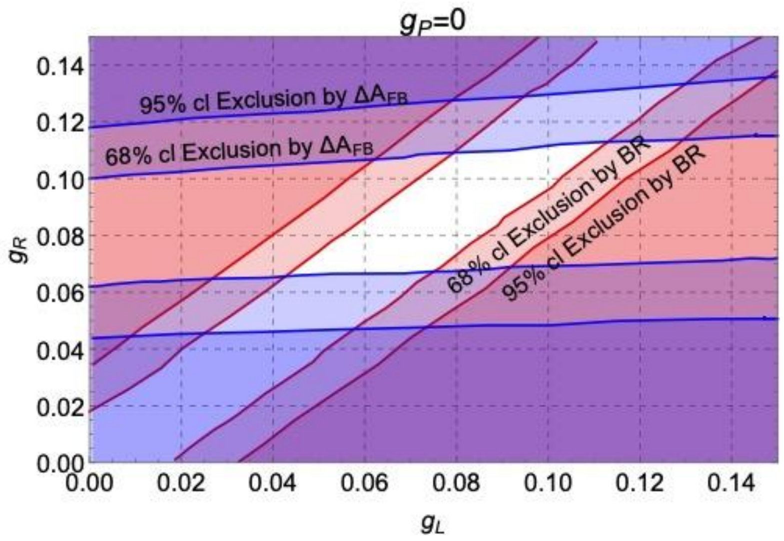
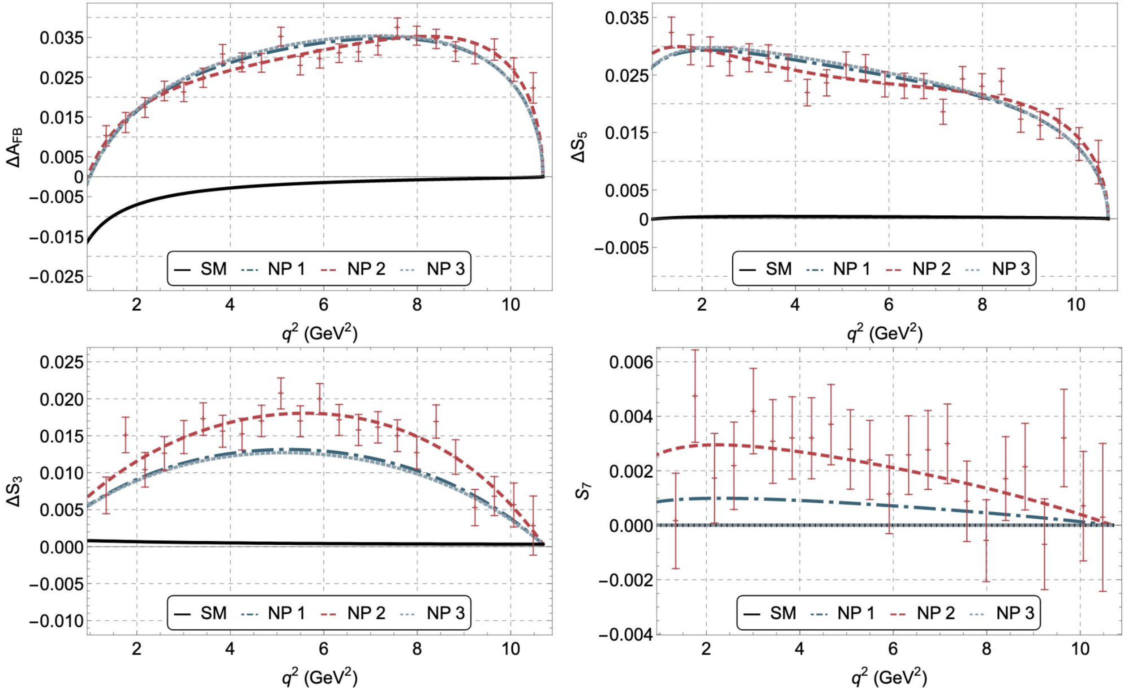
Choosing NP Scenarios

- Used following constraints:
  - BR = $B(B \to D^* \mu\nu)/B(B \to D^* e\nu)$= 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
- In order to satisfy both constraints, must have positive, real g_L and g_R



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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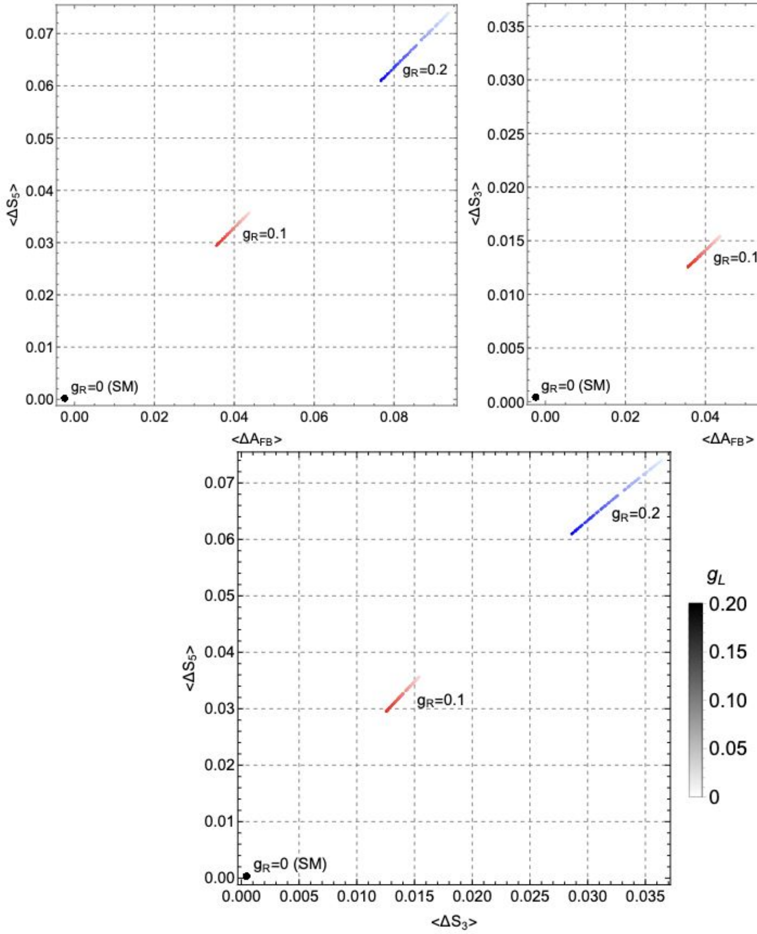

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Cuts

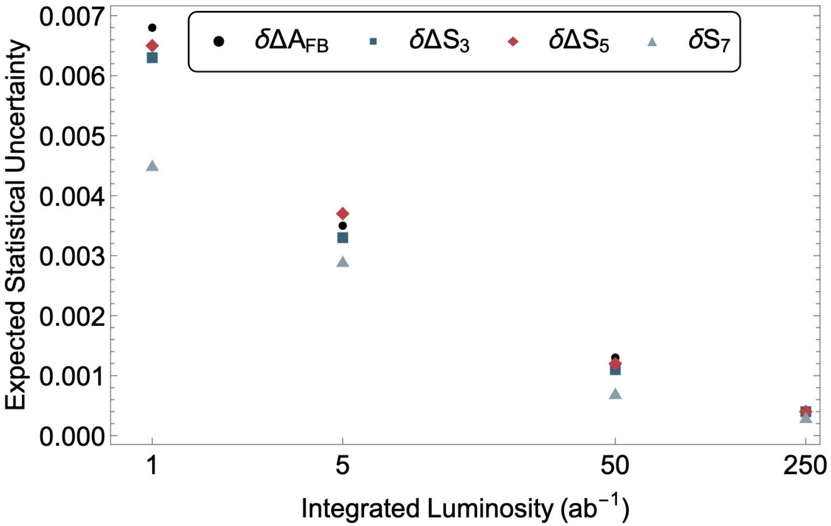
- For our analysis we have used Belle II specifications for the transverse momenta of the lepton and pion, angular acceptance
  - $p_{T,\ell} > 0.8$ GeV
  - $p_{T,\pi} > 0.1$ GeV
  - $-0.866 < \cos\theta < 0.956$ for all final state particles
- We also advocate a low q^2 cut of 1.14 GeV^2 to avoid the large negative value of our angular observables toward the m_ℓ^2 threshold

Integrated Values

- To date, ΔA_{FB} has been analyzed as an "integrated" quantity (using 1 q^2 bin that encompasses the entire desired range)
- Theory predictions of central values are given with estimated theoretical uncertainties
- Statistical uncertainties are given from MC simulations of increasing integrated luminosity

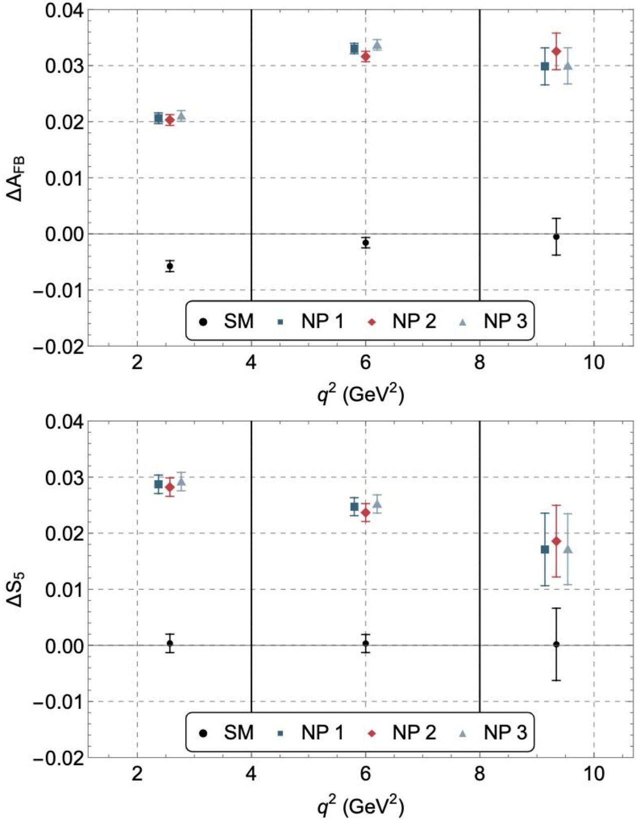
Integrated Δ Observables

	$\langle \Delta A_{FB} \rangle$	$\langle \Delta S_3 \rangle$	$\langle \Delta S_5 \rangle$	$\langle S_7 \rangle$
	%	%	%	$\times 10^{-3}$
SM:	-0.252±0.004	0.0441±0.0007	0.0286±0.0013	0
NP 1:	2.89±0.05	1.08 ± 0.04	$2.44^{+0.02}_{-0.03}$	0.70 ± 0.01
NP 2:	$2.89^{+0.05}_{-0.06}$	$1.49^{+0.05}_{-0.04}$	$2.43^{+0.02}_{-0.03}$	2.0±0.1
NP 3:	$2.94^{+0.04}_{-0.05}$	1.04±0.04	$2.47^{+0.03}_{-0.02}$	0



Coarse-Binned Analysis

- First step to considering q^2 dependence of angular obeservables
- Bin ranges:
  - 1.14 to 4 GeV^2
  - 4 to 8 GeV^2
  - 8 to $(m_B+m_{D*})^2$ GeV^2
- With high enough statistics, it will be possible to perform unbinned fits on the angular observables



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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
- We have developed a MC tool that can generate NP in $B \to D^* \ell \nu$
- The presence of NP requires simultaneous signals in several correlated observables
- Integrated and coarse q^2 bin analyses of these correlated observables can indicate NP with both current and projected data sets
- In the future, unbinned analyses can be performed to more accurately determine the q^2 dependence of the angular observables

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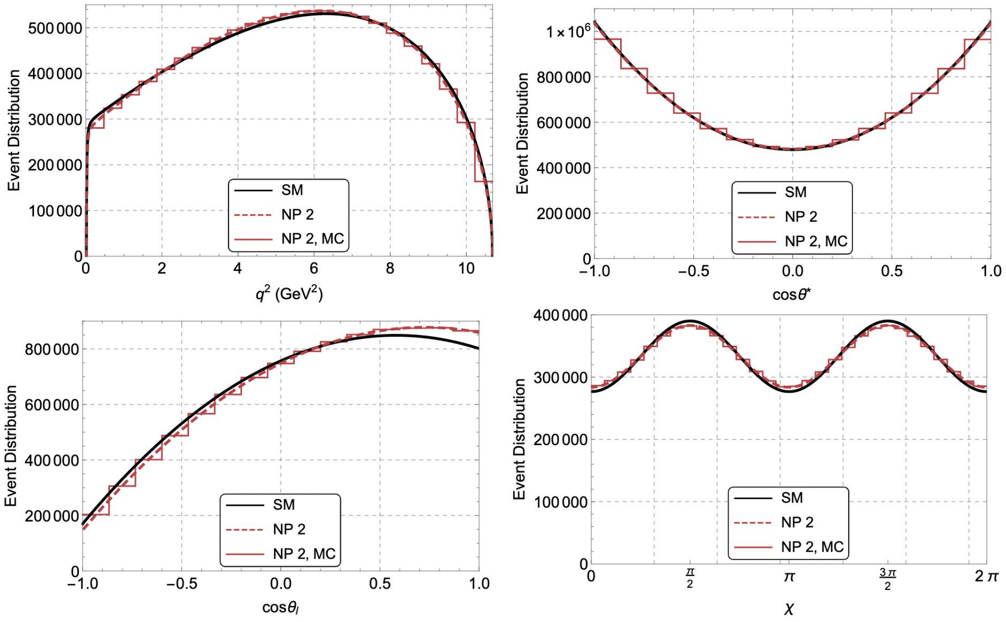
Backup Slides

Kinematic Distributions



Observables

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

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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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